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ALLIS-CHALMERS

THIRD QUARTERLY TECHNICAL PROGRESS REPORT
ON DESIGN OF
HYDROGEN-OXYGEN CAPILLARY TYPE FUEL CELL

15 February 1963

Flight Accessories Laboratory
Aeronautical Systems Division
Wright-Patterson Air Force Base
Dayton, Ohio

Project No. 8173 Task No. 817303

(Prepared under Contract No. AF 33(657)-8970
by Allis-Chalmers Manufacturing Company
Milwaukee 1, Wisconsin)

The work covered by this report was accomplished under Air Force Contract AF 33(657)-8970, but this report is being published and distributed prior to Air Force Review. The publication of this report, therefore, does not constitute approval of the Air Force of the findings or conclusions contained herein. It is published for the exchange and stimulation of ideas.

FOREWORD

This report was prepared by the Space and Defense Sciences Department of the Allis-Chalmers Manufacturing Company, Research Division, Milwaukee 1, Wisconsin, on Air Force Contract AF 33(657)-8970, Project No. 8173 and Task No. 817303. The work was administered under the direction of the Flight Accessories Laboratory, Aeronautical Systems Division, Wright-Patterson Air Force Base, Dayton, Ohio. Mr. Robert L. Kerr is the task supervisor for A.S.D.

The work began on 15 May 1962 on an applied research program for the design, fabrication and test of a 400 watt space oriented fuel cell system.

A significant change in scope of this contract by the Flight Accessories Laboratory, Aeronautical Systems Division, has resulted in a new work statement dated 31 July 1962 calling for an orbital fuel cell experiment.

This report represents the work subsequent to the Second Quarterly Technical Progress Report and covers the period of 1 November 1962 to 31 January 1963, and is being submitted as the Third Quarterly Technical Progress Report as part of the contract commitment.

Management direction at Allis-Chalmers includes Mr. W. Mitchell, Jr., Director of Research, and Mr. D. T. Scag and Mr. W. W. Edens, Assistant Directors of Research. The project is supervised by J. L. Platner, Section Head and P. D. Hess, Chief Engineer. Mr. N. P. Bannerton is the Project Leader. L. Donelan, Senior Engineer, is responsible for engineering design.

The report was written by N. P. Bannerton, R. Chesner, L. E. Donelan, E. L. Laskey and J. C. Prestridge.

ABSTRACT

The testing of two laboratory model fuel cell packages and evaporative cooling studies for thermal management of the package are discussed.

The design of fuel cell Orbital Package No. 1 has been completed and two packages have been fabricated and assembled. Orbital Package No. 1, Serial No. 1, is at A. S. D., Dayton, Ohio, undergoing testing for heat loss investigations at various environmental conditions. Orbital Package No. 1, Serial No. 2, is at Allis-Chalmers Research Laboratories undergoing operational testing prior to environmental qualification tests.

Thermal management studies of the package are continuing.

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1.0 INTRODUCTION

The object of this program is to evaluate the operation of a capillary type hydrogen-oxygen fuel cell while operating in an earth orbit. The Second Quarterly Report under this program discussed the objectives of the program and the center line design of the fuel cell orbital package.

This report covers the completion of Phase I of this program and part of Phase III. Phase I consisted of preliminary investigation of the design and fabrication of a fuel cell orbital package.

Phase III has been started and will consist of the operational testing of the orbital package and performance of the environmental qualification tests. During this phase a second orbital package will be designed and fabricated based on information gained from the environmental testing.

Phase IV provides for the integration of a fuel cell package into a launch vehicle and the interpretation of telemetered data from the mission to evaluate the fuel cell performance.

Phase II runs concurrently with the other phases and will correlate information gained during the program into a composite conceptual design of the capillary fuel cell for a space vehicle electrical energy source.

2.0 LABORATORY EXPERIMENTS

Preliminary investigation of a capillary type fuel cell for an orbital experiment consisted of the design and construction of two laboratory models to test the performance, control and the cooling system. The design and construction of these models were described in the Second Quarterly Report. Two units of Model No. 1, Serial Nos. 1 and 2, were fabricated as shown in Figures 1 and 2. Serial No. 1 was checked for performance in the Allis-Chalmers Research Laboratories and then sent to A. S. D. Dayton, Ohio for motion tests. Serial No. 2 was used in the laboratory mainly for a series of tests using evaporative cooling to absorb the heat generated in the fuel cells.

2.1 Orbital Fuel Cell Package, Laboratory Model No. 1

The first unit Serial No. 1 of this model fuel cell was initially tested at the Allis-Chalmers Research Laboratories on 22 and 23 October 1962 for performance and the data is shown in Tables 1 and 2. The unit was delivered to A. S. D. for vibration, shock and acceleration tests, which were carried out at room temperature, between 16 November and 14 December 1962. For these tests the water tank was filled with water (approximately 15 pounds) and the total weight of the package was 36.5 pounds. The 15 pounds of water was estimated sufficient for 5 days operation. Length of the fuel cell experiment was later reduced to approximately 52 hours, thereby reducing the tank size and weight of water proportionally. Serial No. 1 of Model No. 1 was later returned to Allis-Chalmers Laboratories for performance testing, the results of which are shown in Table 3.

2.1.1 Performance Tests

The electrical capacity test performed on 22 and 23 October 1962 were the first tests on a package configuration. It was apparent that the package was suffering from insufficient compression upon the cells.

Additional clamping by using "C" clamps markedly improved the cell performance. Data shown in Tables 1 and 2 was obtained with the package clamped.

The package capacity on 22 October 1962 was 49.4 watts at 1.52 volts and on 23 October was 53.2 watts at 1.66 volts. Improvement in capacity of the 23 October 1962 test probably was due to variation in the uniformity of clamping.

These tests served as the prior operation tests subsequent to motion testing.

2.1.2 Vibration Tests

Vibration test of Serial No. 1, Model No. 1, was carried out by using the mounting holes in the hydrogen end plate for attaching the package to the vibration test jig which in turn was fastened rigidly to the shaker table. An M. B. C-25H vibration shaker system was used to provide the dynamic inputs. The lower frequency (5 - 14 cps) vibration test was not carried out. Inputs were:

Frequency, cps	Acceleration
14 to 400	$\pm$ 5.0 g
400 to 2,000	$\pm$ 7.5 g

Maximum output responses of the package were recorded using Endevco Model 2226 accelerometers. These outputs are shown in Figures 3, 4 and 5 for the three axes. The position of the package during each test is shown on the respective curve. No noticeable resonance or damage to the package occurred during these tests.

2.1.3 Shock Test

Following vibration test, the fuel cell package was subjected to three impact shocks in each direction along each of the three mutually perpendicular axes using the same mounting arrangement. A total of eighteen shocks were imposed, each shock having an intensity of 40 g's and a time duration of 8 milliseconds. The half sine pulse wave form showed the intensity and time duration of the shock. A Barry Varipulse shock machine was used for the shock tests.

No noticeable damage occurred to the package during these tests.

2.1.4 Acceleration Test

The acceleration test of the fuel cell package was carried out on a centrifuge. The 10 minute accelerations were 15 g perpendicular to the plane of the fuel cell and 2.5 g parallel. No noticeable damage occurred to the package during these tests.

2.1.5 Conclusions

Motion tests were performed to determine if the capillary type fuel cells in package configuration would be susceptible to damage during the launch period of an orbital mission. The performance tests that preceded and followed the motion tests were conducted at various levels of load from 10 watts to 80 watts to determine the effect of the motion tests. Contract requirement is for a 2 cell package producing 35 watts output. However, the cells were designed for 50 watts.

The post motion operational test on 16 January 1963 (Table 3) showed no deterioration in cell performance when compared to the 22 October 1962 performance test. Comparison of the post operational test with the 23 October 1962 performance test shows about an eight percent difference in capacity. These comparisons are shown below.

Prior Tests			
	22 October 1962	1.52 volts	49.4 watts
	23 October 1962	1.66 volts	53.2 watts
Post Tests			
	16 January 1963	1.53 volts	49.0 watts

The reduced capacity of the post test over the second prior test does not necessarily indicate a loss in performance of the cells as the motion tests were performed with the gas manifolds inadvertently left open to the atmosphere and the time interval between operational tests was quite long (twelve weeks). There were no other indicated failures or damage, and this series of tests was considered satisfactorily concluded.

2.2 Evaporative Cooler Tests

Model No. 1, Serial No. 2 fuel cell package was constructed and tested for electrical output as described in the Second Quarterly Report. This package was then used for two evaporative cooler tests.

2.2.1 Tube Type Cooler

In November a test was conducted for a short period with the originally designed evaporative cooler. This consisted of a tank containing water that would be expelled by a bladder through small holes into a tube surrounding the cells and then exhausted to space vacuum through a relief type valve. The outside of the tube was covered with asbestos and it was planned that the evaporation of the water would take place at the surface of the asbestos when the relief valve was vented at the vapor pressure of the water and the desired temperature of 200°F.

2.0 Continued

Some difficulty was initially encountered with the relief valve sticking. After cleaning and freeing up the relief valve, the system operated satisfactorily, maintaining a cell temperature of 205°F. for a period of several hours before it was shut down for the week end. When the package was restarted, it was found that the asbestos surrounding the perforated tube in the cooling annulus had become hard and dry and was completely blocked. This condition resulted from the use of an impure grade of asbestos. This test was terminated and the cooling system modified for the next test.

2.2.2 Absorbent Cotton Cooler

The second cooler test with Serial No. 2 package consisted of a new design water storage tank filled with water saturated cotton and bolted directly to the base plate, see Figure 6. The cotton was pressed against the cells and held in place with a fine screen. A controlled pressure space was left at the top of the tank for the water vapor. Venting of this space to a vacuum was controlled by a thermostatically operated solenoid valve during the first test, see Figure 6. Although the cooler was not attached to the cell in the most advantageous way, from a heat transfer standpoint, it was possible to maintain temperature gradient across the cell within 10°F at almost a constant mean temperature. This control was tested with the cooler dissipating 80 watts in excess of the heat loss through the insulation. The cooler control was modified in the second test, Figure 7. The thermostatically controlled solenoid valve was replaced by a pressure controlling relief valve for venting the cooler. Since pressure control within the cooler also controls the temperature of the cooler, it was merely necessary to adjust the relief valve until the cell temperature was maintained at the desired level. This method proved to be equally as satisfactory as the thermostatic control.

This series of tests proved that an evaporative cooling system could be used to absorb the heat produced by the fuel cells and uniformly control the temperature. Studies and tests in the use of this method of evaporative cooling are continuing.

2.3 Orbital Fuel Cell Package Laboratory Model No. 2

Laboratory Model No. 2 as described in the second Quarterly Report was assembled and performance tested. The electrical output of this model was similar to that of No. 1. It was found that the performance of both Models No. 1 and 2 could be improved by a more uniform clamping across the cell area. Model No. 2 was used for further cooling and temperature control testing and for operational testing of package components considered for the final orbital package design. Figure 8 shows a photograph of Model No. 2.

2.3.1 Flash Evaporative Cooler Tests

Tests were made to evaluate the ability of two flash evaporative cooler plate configurations to remove excess heat and maintain the fuel cell at a constant temperature when operated at a reduced pressure. A bellows-type pressure relief valve was used to control the cooler pressure, see Figure 9. The flow of water to the cooler was controlled by an expanding liquid type valve. See Figure 10.

Temperatures were recorded by thermocouples which were attached to the cooler, the temperature control valve, the water storage tank and the cooler outlet tubing.

2.3.2 Straight Slot Design

Test on this design consisted of test runs at total power inputs of 30, 50, 75, 100 and 125 watts. The length of each run was 2 hours. Prior to the start of the test runs, heat loss through the insulation was determined to be 20 watts.

Test results indicate cooling at all points on the cooler. The following table summarizes the temperature management results of this test.

MAXIMUM TEMPERATURE VARIATIONS (On Cooler)

Cooler Heat Burden	Any Thermocouple	All Thermocouples
30 watt	0.5°F	4.3°F
50 watt	2.7°F	9.8°F
75 watt	0.9°F	9.3°F
100 watt	9.5°F	17.3°F
125 watt	9.0°F	15.6°F
Entire test	10.9°F	18.0°F

The test was made with a higher vacuum on the cooler than was desired. The flow of water through the temperature control valve was excessive and the increased vacuum was necessary to prevent flooding of the cooler with liquid water. This increased vacuum caused some subcooling and resulted in increased temperature variation. Operation of the temperature control valve became increasingly erratic as the power input increased. During the 75 watt run, some liquid water was drawn from the cooler. Flow of liquid water increased during the 100 watt run. Weight loss was large during the first hour of the 125 watt run. This was due to flooding of the cooler several times by the temperature control valve.

Primary objective of the test, the feasibility of flash evaporation cooling, was achieved even though the temperature variation was higher than desired. It appears that the variation was due to the erratic operation of the temperature control valve which was not the valve design to be used in Orbital Package No. 1. This test was discontinued to try a different evaporator plate design.

2.3.3 Diagonal Slot Design

Test on this design was similar to the test on the straight slot design except the slots were diagonally across the plate and the insulation loss was 28 watts.

Results of this test indicate cooling at all points on the cooler. The following table summarizes the temperature test results.

MAXIMUM TEMPERATURE VARIATIONS (On Cooler)

Cooler Heat Burden	Any Thermocouple	All Thermocouples
35 watt	2.0°F	2.4°F
50 watt	7.2°F	9.7°F
75 watt	9.0°F	13.2°F
100 watt	15.0°F	15.0°F
125 watt	16.5°F	19.8°F
Entire test	23.6°F	25.1°F

Operation of the temperature control valve was erratic throughout the test. Observation during the test indicated that the valve would open properly for several cycles and then would stick allowing the temperatures to rise several degrees before opening. Upon opening, the valve would over-travel allowing an excessive flow of water to the cooler. This condition required operation at a higher cooler vacuum which caused some subcooling. Liquid water was drawn from the cooler during all runs with the amount increasing as the power input increased.

This cooler design was also satisfactory for removing excess heat and maintaining a fuel cell at a constant temperature. While the temperature variation was higher than that for the straight slot design, this increase appears to have been caused by the less satisfactory operation of the temperature control valve.

2.0 Continued

The very small flow of water required to the evaporator plate for this heat load is the limiting factor for control within the temperature ranges desired. This series of tests were discontinued in favor of the tests on Orbital Package No. 1.

3.0 ORBITAL PACKAGE NO. 1

Considerable time was spent in the third quarter in the design of Orbital Package No. 1 to include the improvements indicated by the tests on the two laboratory models. The first unit Serial No. 1 of this model was assembled and tested.

Tests were successful in proving the suitability of the cell construction by obtaining rated fuel cell performance, but some difficulty was experienced with the auxiliary equipment, especially the solenoid valves. Space oriented auxiliaries were not available and as such these troubles were expected. With the availability of this package a decision was made to substitute this package for the heat loss testing at ASD in place of the scheduled Laboratory Model No. 2. Orbital Package No. 1, Serial No. 1, was shipped to Dayton on 11 January 1963. The results of these tests will be reported in the next Quarterly Report.

Orbital Package No. 1, Serial No. 2 was constructed and checked out before being mounted in the test fixture on 30 January 1963. The fixture and package was insulated and prepared for testing prior to environmental testing. New manifolds were included in this package to use the type of solenoid valves intended for use in the final package. The arrangement and size of this system is indicated by Figures 11 and 12.

Design of Orbital Package No. 1, see Figure 12, resulted from a number of changes in Model No. 2 shown in the Second Quarterly Report. A diagram of the system is shown in Figure 13. One of the major changes was in the water storage tank for the cooling system. Another was separate gas manifold blocks to allow the space oriented components to be adopted when they became available. The components selected for this package and the other modification to Model 2 are listed below.

3.0 Continued

3.1 Components Selected

3.1.1 Thermostatic relays for temperature control of the fuel cell package were tested and found to operate satisfactorily in a laboratory set-up. Six sets were obtained from G. V. Controls, Inc. and are arranged in matched pairs set to maintain fuel cell temperature in the range of 190°F to 200°F by application of cooling and heating with a 4°F dead band between heater and cooler operation.

3.1.2 Pressure transducers were obtained from the Colvin Laboratories Inc. and should be suitable for our application. Additional transducers for the orbital packages were ordered to our specification 1-SK-62309-2. Two transducers failed to date from apparent over pressure.

3.1.3 Solenoid valves to our specification 1-SK-62284-1 were ordered from The Weatherhead Company. Back-up valves are being ordered from Whittaker Controls and Guidance Company, (Division of Telecomputing Corporation).

3.1.4 Absolute Pressure Regulators to our Specification 1-SK-62296-3 were ordered from the Scott Aviation Company with a back-up regulator ordered from the Firewel Company.

3.1.5 Zero pressure reference relief valves have been ordered from the Scott Aviation Company. Absolute pressure relief valves have been ordered from the Firewel Company.

3.1.6 Explosive valves to our specification 1-SK-62289-1 have been ordered from Conax Corporation.

3.1.7 Explosive switches to our specification 1-SK-62288-3 have been ordered from the Atlas Chemical Industries.

3.0 Continued

3.1.8 Load relay for switching the load were obtained from Guardian Electric. These relays were satisfactorily tested in our laboratory for a week continuously.

3.2 Design Changes from 2nd Quarterly Report

A number of minor design changes have been made in the last quarter and they are listed herein for record purposes.

3.2.1 The wax used to impregnate the edges of the asbestos electrolyte holders has been eliminated. An improved method of sealing has been obtained with regular gasket material. This provides a a second advantage of eliminating possible wax flow under excessive temperatures.

3.2.2 Fuel cell end plates and manifolds were redesigned for weight reduction. This involved the removal of the double sealing in favor of the single sealing method which in turn allowed for reduction in plate size. The same mounting method and dimensions were maintained. Some reduction in size and weight of the manifolds was obtained by a reduction in size of explosive valve and rerouting of the flow arrangements.

3.2.3 Voltage Controller

Four units of the voltage controller described in the Second Quarterly Report were assembled. These units have been used to control the hydrogen and oxygen solenoid exhaust valves during the testing of the fuel cell packages. Operation of these controllers has been satisfactory. However, the units were designed and built to use germanium transistors, which are not considered suitable for space application. A new model using silicon transistors has been breadboarded and satisfactorily tested at room temperature.

3.0 Continued

3.2.4 Some minor changes were made in the fuel cell wiring and temperature control diagram from the Second Quarterly Report. The latest diagram is as shown in Figure 14.

4.0 INTERFACE RELATION WITH VEHICLE CONTRACTOR

Meetings with the vehicle contractor have supplied interface matching between the two organizations without difficulties but a few points yet remain to be resolved. In general, the interface has been established on the cell itself with the vehicle manufacturer supplying the reactant, venting and tubing to the cell. This coupling tubing will be 1/4 inch. Electrical interface shall be at connectors with each organization supplying half of the connector. Mechanical mounting shall be by means of 5 bolts on each side of the cell. The cell shall be thermally isolated from the vehicle. A temperature environment will be established on an enclosure surrounding the fuel cell.

4.1 Thermal Management Studies of Orbital Package

A number of methods could be used for temperature control of the fuel cell module in orbit. The method to be used must be the most suitable considering the numerous uncertainties of the installation at this time.

The first method analyzed entailed the study of a fuel cell module while exposed to incident heat fluxes in orbit (uncontrolled environment). The fuel cell would be insulated from thermal conduction to the vehicle. A layer of insulation would be utilized along with a surface finish mosaic to provide radiant thermal control of the system when exposed to a wide range of heat fluxes in space. To maintain the fuel cell package temperature, thermostats would be used to switch the cell electrical power output to either internal heaters or external load resistors.

In this analysis, two equations are needed:
The first describes the rate equation for energy transferred through the insulation.

(1) - - - $Q_{internal} = Q_c + Q_{aux} + Q_{elect} = \frac{K}{\Delta X} A_c (T_c - T_s)$

Q_c = energy dissipated in the fuel cell due to its inefficiency, 78.5 Btu/hr.

Q_{aux} = auxiliary power from components, such as solenoids, which is dissipated internally, 34.0 Btu/hr.

Q_{elect} = average electrical power dissipated in internal heaters, Btu/hr.

$\frac{K}{\Delta X}$ = $\frac{\text{thermal conductivity of insulation,}}{\text{mean conduction path length}}$ $\frac{\text{Btu}}{\text{hr ft}^2\ {}^\circ\text{F}}$

A_c = mean conduction area through 1" insulation, 3.21 ft^2

t_c = cell temperature, 200°F.

t_s = surfact temperature of insulation, °F.

This equation indicates the surface temperature of the insulation to allow the internal energy dissipated in the cell to be removed by conduction to the surface of the insulation. Figure 15 is a plot of equation 1 for various values of internal heater power.

The second equation is an energy balance at the surface of the insulation. Energy dissipated within the cell plus the energy absorbed from sun must equal the energy radiated to space.

(2) - - - $Q_{internal} + Q_{external} = \sigma A_r F_A F_e T_S^4$

$Q_{external}$ = αA_p S.C. (Assuming the solar input is the only significant heat rate)

α = Solar absorptivity of surface

A_p = Projected area for solar 1.26 ft^2

S.C. = Solar constant, 443 Btu/hr ft^2

σ = Stefan Boltzman constant, .173 x 10^{-8} Btu/hr ft^2 °R^4

A_r = Surface area of 1" insulation 4.03 ft^2

F_A = View factor to space, 0.7

F_e = Emissivity factor to space = (ϵ) emissivity of surface = 0.9

T_s = Surface temperature of insulation, °R

$Q_{internal}$ as defined in equation (1), Btu/hr

This equation establishes the surface temperature of the insulation based on a net heat flux of zero. Figure 16 depicts the surface temperature as a function of external heat rate for various average internal heater powers. (Note that any significant heat flux from the vehicle can be lumped with the solar input to obtain Q external.)

With figures 15 and 16 available, to obtain a solution, consider the following example.

(1) Decide on the maximum amount of average power to be dissipated internally, e.g., 20 watts. (2) From Figure 16 determine the surface temperature of the insulation when the external heat rate is zero for the given internal power, for 20 watts t_s = -10°F. (3) From Figure 15 determine the conduction factor which corresponds to t_s obtained above, $K/\Delta X$ = 0.28 Btu/hr ft^2 °F. (4) Knowing the conduction factor, draw a vertical line at that value. The surface temperatures can then be obtained for all internal power levels at the intersections of the parametric curves. (5) Cross plot t_s versus internal power on Figure 16. The resulting dashed curve shown describes the amount of heater power needed for any given external heat rate. External heat rate must be held below the amount corresponding to the surface temperature when the internal heater power is zero. In this case, the surface temperature is 65°F.

This means that the required surface finish must have an absorptivity of less than 0.4 so that Q external does not exceed 66 watts.

The above method of control would prove to be satisfactory but requires much detail information on installation, orientation of the module relative to the sun while in orbit, etc. At this time such information is not available. The vehicle contractor has agreed to provide an enclosure around the fuel cell package, the internal surface temperature of which will not vary outside the limits of -30°F to +165°F specified in the design contract. Emissivity of the inside surface of the enclosure is to be at least 0.8. Thermal design will therefore be based on that environment.

The vehicle contractor will supply the reactant gases within the same temperature range. Amount of internal energy which will have to be dissipated from the cell will vary with the supply gas temperature since some of the power lost in the cell will be used to heat the gases to the cell temperature. Operating at 50 watts output, at an inlet temperature of -30°F, the energy dissipated internally will be 22 watts and at 165°F the energy dissipated internally will be 28 watts.

Having established the environment in which the fuel cell will be operating, an analysis was made to determine if some thickness of insulation could be used to control the cell temperature with 35 watts (guaranteed fuel cell electrical output) of switchable heater power. When the surroundings are at 165°F, the 22 to 28 watts of internal power plus 10 watts of auxiliary power will have to be dissipated. It was found that the amount of insulation needed was insufficient to maintain the cell at 200°F when the surroundings are at -30°F and 35 watts are switched internally.

Use of an evaporative cooler without internal heaters was then considered. Sufficient insulation could be provided for the fuel cell package to insure that, regardless of the environmental temperature, more energy would be produced internally than would be needed to maintain the cell temperature. Excess energy could then be absorbed by an evaporative cooler. This method is quite feasible but the analysis indicated that the extra weight of insulation plus cooling water would be excessive.

At this point it was decided to investigate a combination heater and cooler system using various surface finish mosaics on the fuel cell surface without insulation.

Since the vehicle contractor has agreed to provide a well insulated mounting, thermal resistance at least 40 $\frac{°Rhr}{Btu}$, the conduction losses should be less than 6 Btu/hr and may be neglected. The control problem now becomes a radiation interchange supplemented by heating or cooling as required.

The following expression describes the net radiation from the fuel cell to the enclosure.

$$(3) - - - Q_{radiation} = A_S F_A F_E \ (T_c^{\,4} - T_{ext}^{\,4})$$

$$F_e = \text{emissivity factor } \frac{1}{\frac{1}{\epsilon_c} + \frac{1}{\epsilon_{ext}} - 1}$$

ϵ_c = emissivity of cell

ϵ_{ext} = emissivity of enclosure, 0.8

T_{ext} = enclosure temperature, °R

T_c = cell temperature, 660°R (200°F)

A_s = surface area of the fuel cell module including cooler tank, no insulation, 3.0 ft^2

F_A = view factor to enclosure, 1.0

The energy balance on the cell would be

$$(4) \; - - - \; Q_{radiation} = Q_c + Q_{aux.} + Q_{control}$$

Q_c and Q_{aux}, as defined for equation (1).

$Q_{control}$, if positive, represents heater power required to maintain the cell at 200°F. If negative, it represents the cooling load on the evaporative cooler.

Figure 17 summarizes the results obtained by solving equations 3 and 4. Heating and cooling requirements are given in watts on the left ordinate as a function of the enclosure temperature for various emissivity factors. On the right ordinate are given the corresponding net radiation from the cell and the cooling water required for a 52 hr. mission. (The latent heat of vaporization used was 985 Btu/lb.) Since 35 watts of continuous electrical power output is all that is guaranteed, and since a minimum amount of water should be carried, Figure 16 shows that an emissivity factor of approximately 0.25 would be most suitable.

This means that with an enclosure whose emissivity is 0.8, the effective emissivity of the fuel cell should be 0.27. This finish can be obtained by a mosaic of approximately 70 percent aluminum foil and 30 percent black acrylic paint. If the surface temperature of the cell and tank vary significantly, the mosaic can be adjusted to give the desired integrated effect.

An analysis was made to determine if a layer of insulation plus a mosaic finish would prove to be a better complement to the thermal control system, using both heaters and cooler. In all cases investigated the total weight of the control system increased. In addition to the insulation weight, a larger amount of cooling water was required. Minimum increase in weight over the previous method was found to be greater than 1.0 pound. There are some advantages to this heavier system in that less heater power will be needed to maintain the cell at 183°F on the launch pad while being convectively cooled. Also, a more uniform surface temperature over the outside of the package will be obtained in orbit.

It appears that the most satisfactory system would use no insulation. The package then is lighter, and a minimum amount of cooling water is also required. This is due to the cell being easier to cool at higher environmental temperatures. Using the control described by Figure 17, it is significant to note that almost no active control will be required when the enclosure temperature is near the middle of its allowable range.

Work is being continued on the thermal design to establish the temperature profile of the module in a space environment, the required surface finish mosaic, and the response of the system.

5.0 SCHEDULE

A revised Technical Position Chart is shown in Figure 18, as per letter to Aeronautical Systems Division, Dayton, Ohio, dated 29 October 1962.

Testing at Allis-Chalmers Research Laboratories and at A. S. D. has continued as shown under Items 1 and 2.

Phase II was started on 1 November 1962 as indicated.

For Item 4, design of Preliminary Laboratory Fuel Cell Package, two model packages were constructed and tested.

Operational tests were performed on the two model packages and Model No. 1 was motion tested at A. S. D.

A revised design specification for Orbital Package No. 1 was completed in mid December 1962 as shown in Item 7.

Preliminary testing of Orbital Package No. 1, Serial No. 1, was started in December 1962 and this package was sent to A. S. D. in January 1963. Orbital Package No. 1, Serial No. 2 was constructed in January 1963, and prepared for environmental testing in February.

Fabrication of Orbital Package No. 2 has not been started.

6.0 FUTURE WORK

Environmental testing of Orbital Package No. 1 is scheduled to begin in February 1963. This testing will be conducted throughout most of next quarter. Modification of the fuel cell packages will be carried out as required. Operational testing of fuel cell packages will continue.

Component testing and evaluation will continue.

LABORATORY FUEL CELL PACKAGE MODEL NO. 1

ELECTRICAL CAPACITY PERFORMANCE TEST

22 October 1962

Time (Hrs)	V_1	V_2	V_T	Amps	Watts
0.00	.81	.80	1.61	21.0	33.8
0.07	.81	.80	1.61	21.0	33.8
0.12	.81	.805	1.615	21.0	33.9
0.15	.805	.802	1.607	21.0	33.8
0.23	.81	.805	1.615	21.0	33.9
0.30	.81	.805	1.615	21.5	34.7
0.37	.81	.805	1.615	21.5	34.7
0.48	.81	.805	1.615	21.5	34.7
0.56	.812	.81	1.622	21.5	34.8
1.10	.815	.81	1.625	21.5	34.9
1.12	.76	.76	1.52	32.5	49.4
1.15	.76	.76	1.52	32.5	49.4
1.23	.76	.76	1.52	32.5	49.4
1.27	.758	.762	1.52	32.5	49.4
1.30 *	.879	.875	1.754	10.0	17.54
	.826	.824	1.65	20.0	33.00
	.782	.78	1.562	30.0	46.86
	.74	.735	1.475	40.5	59.70
	.703	.702	1.405	50.0	70.25
1.35	.822	.80	1.622	20.0	32.44

Cell Temperature: 200°F ± 5°F

Cell Pressure: 10.0 psig ± 0.2 psi

*Check on voltage versus ampere output.

TABLE 1

LABORATORY FUEL CELL PACKAGE MODEL NO. 1

ELECTRICAL PERFORMANCE TEST

23 October 1962

Time (Hrs)	V_1	V_2	V_T	Amps	Watts
0.00	.85	.825	1.675	32.0	53.6
0.11	.845	.83	1.675	32.0	53.6
0.20	.845	.83	1.675	32.0	53.6
0.25	.84	.825	1.665	32.0	53.3
0.45	.84	.822	1.662	32.0	53.2
0.50	.822	.815	1.637	34.0	55.6
0.55	.82	.818	1.638	34.0	55.6
1.00	.82	.82	1.64	34.0	55.8
1.02 *	.917	.91	1.827	10.0	18.27
	.87	.86	1.73	21.0	36.3
	.84	.83	1.67	30.0	50.1
	.805	.795	1.60	42.5	68.0
1.10	.77	.76	1.53	56.5	86.5

Cell Temperature: 200°F ± 5°F

Cell Pressure: 10.0 psig ± 0.2 psi

*Check on voltage versus ampere output.

TABLE 2

LABORATORY FUEL CELL PACKAGE MODEL NO. 1

ELECTRICAL CAPACITY TEST

16 January 1963

Time (Hrs.)	V_1	V_2	V_T	Amps	Watts
0.00	.788	.813	1.60	11.0	17.6
0.05	.794	.817	1.61	11.0	17.7
0.15	.808	.824	1.63	11.0	17.9
0.30	.822	.829	1.65	11.2	18.5
0.30	.792	.800	1.59	15.0	23.8
0.45	.790	.800	1.59	15.0	23.8
1.00	.792	.800	1.59	15.0	23.8
1.15	.784	.797	1.58	15.0	23.7
1.20	.784	.797	1.58	15.0	23.7
1.20	.733	.757	1.49	20.0	29.8
1.30	.744	.760	1.50	20.0	30.0
1.45	.757	.765	1.52	20.0	30.4
2.00	.751	.765	1.51	20.0	30.3
2.15	.758	.767	1.52	20.0	30.5
2.30	.747	.765	1.51	20.0	30.3
3.00	.746	.770	1.52	20.0	30.5
3.30	.741	.773	1.51	20.0	30.3
4.00	.803	.806	1.61	20.0	32.2
4.30	.824	.834	1.65	15.0	24.9
5.00	.828	.818	1.65	15.0	24.7
5.30	.874	.831	1.70	15.0	25.5
5.70	.848	.799	1.65	20.0	32.9
6.00	.834	.796	1.63	20.0	32.6
6.30	.808	.794	1.60	20.0	32.0
7.00	.755	.789	1.54	20.0	30.8
7.30	.753	.787	1.53	20.0	30.6
8.00	.744	.791	1.53	20.0	30.6
8.30 *	.597	.854	1.45	12.0	29.0
8.55	.863	.797	1.66	20.0	33.3
9.00	.861	.796	1.66	20.0	33.3
9.75	.865	.793	1.66	20.0	33.3
9.15	.841	.758	1.60	25.0	40.0
9.30	.844	.762	1.60	25.0	40.4

* Oxygen restriction on Cell No. 1 was closed.

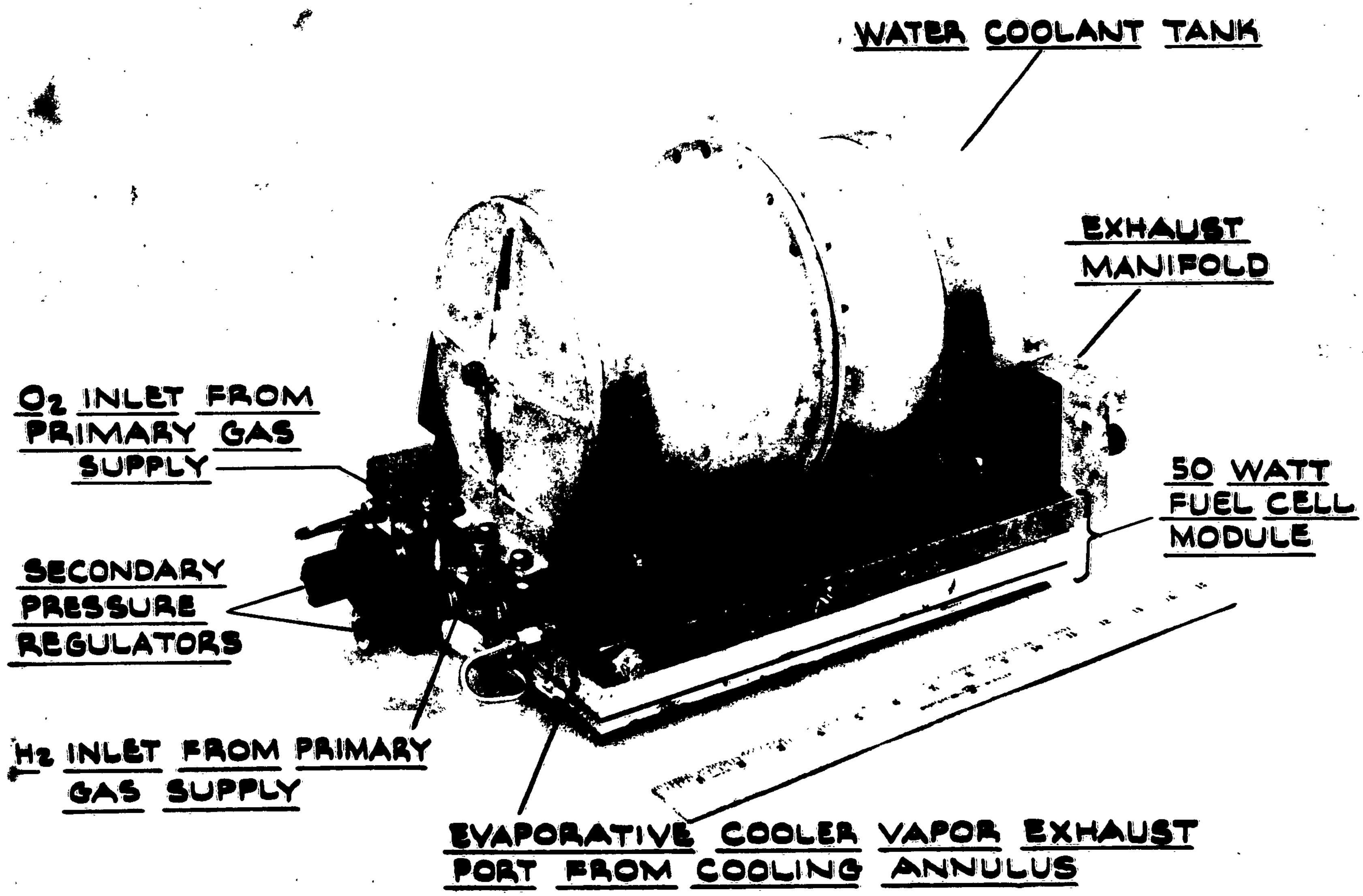
TABLE 3

TABLE 3 CONTINUED

Time (hrs)	V_1	V_2	V_T	Amps	Watts
10.00	.839	.769	1.60	25.0	40.3
10.00	.818	.736	1.55	30.0	46.6
10.30	.818	.730	1.55	30.0	46.6
10.45	.821	.729	1.55	30.0	46.6
10.46	.796	.696	1.50	35.0	52.2
10.47	.812	.722	1.53	31.5	48.4
10.50	.806	.714	1.52	32.0	48.6
11.00	.813	.718	1.53	32.0	49.0
11.10	.823	.722	1.55	32.0	49.6
11.15	.818	.717	1.54	33.0	50.8

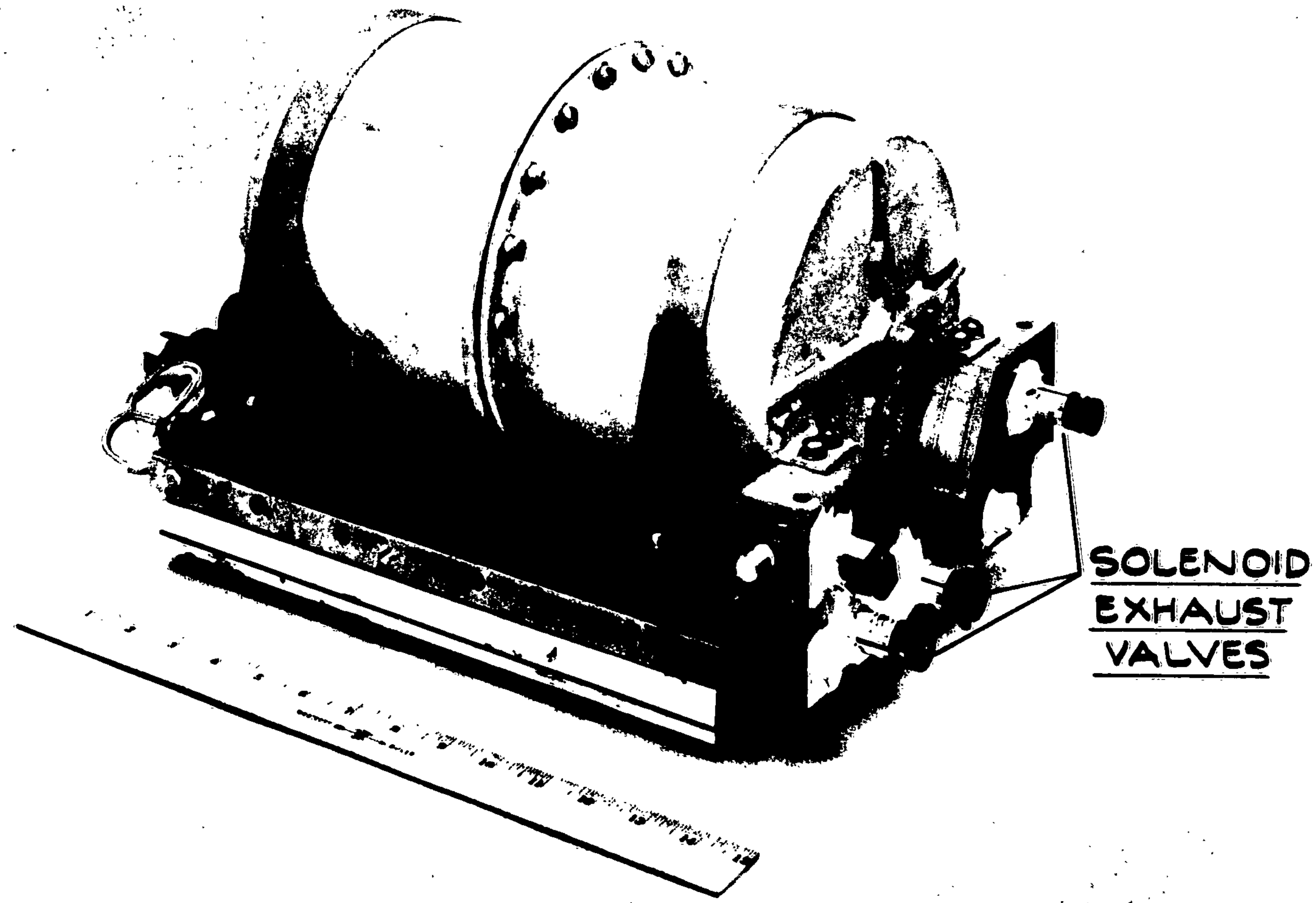
Cell temperature - 200°F ±5°F

Cell Pressure - 10.0 psig ± 0.2 psi



ORBITAL PACKAGE LABORATORY MODEL NO. 1 SERIAL NO. 1

Figure 1



ORBITAL PACKAGE LABORATORY MODEL NO. 1 SERIAL NO. 1

Figure 2

VIBRATION TEST
ACCELEROMETER MAXIMUM OUTPUT

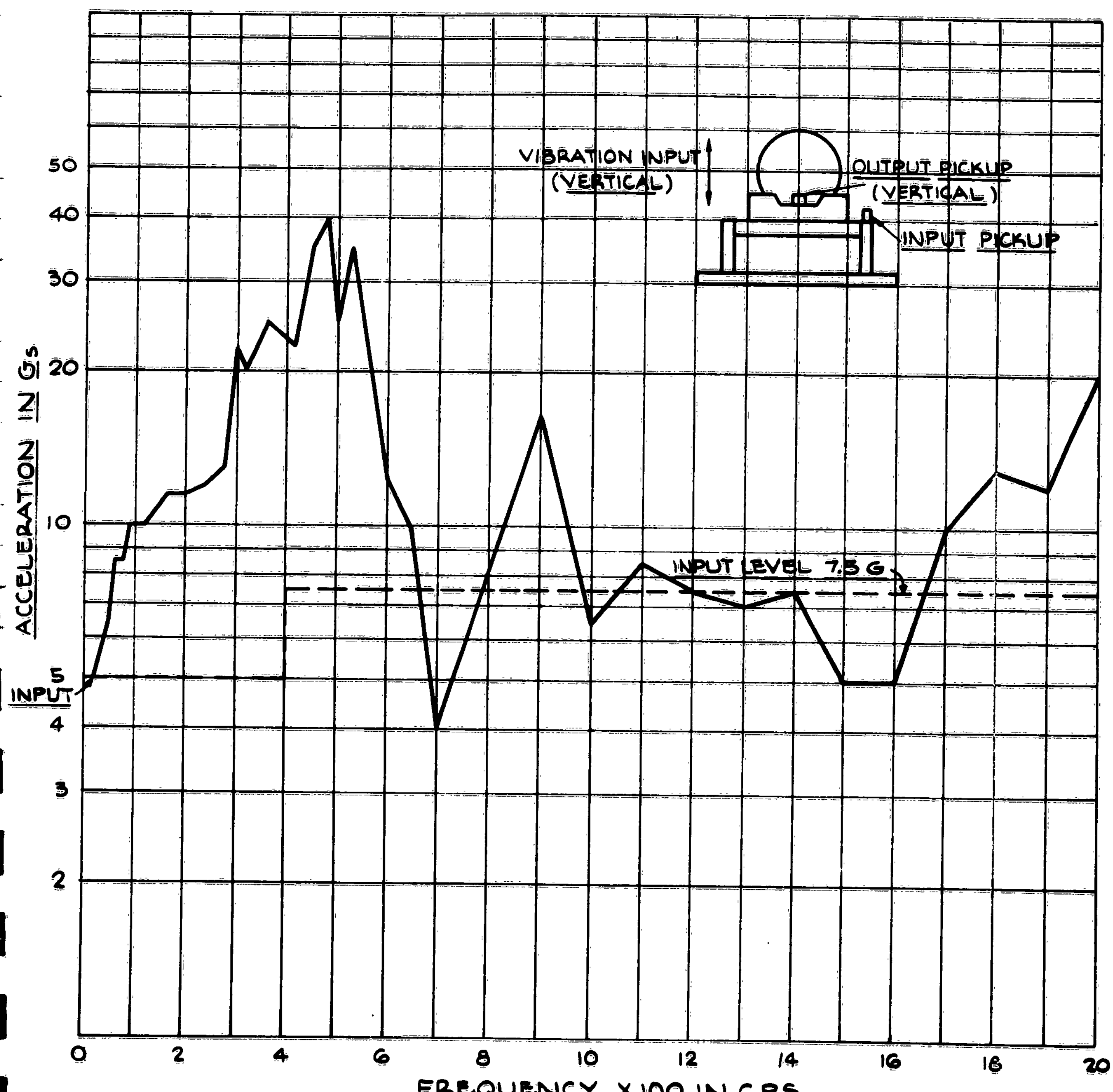


FIGURE 3

VIBRATION TEST
ACCELEROMETER MAXIMUM OUTPUT

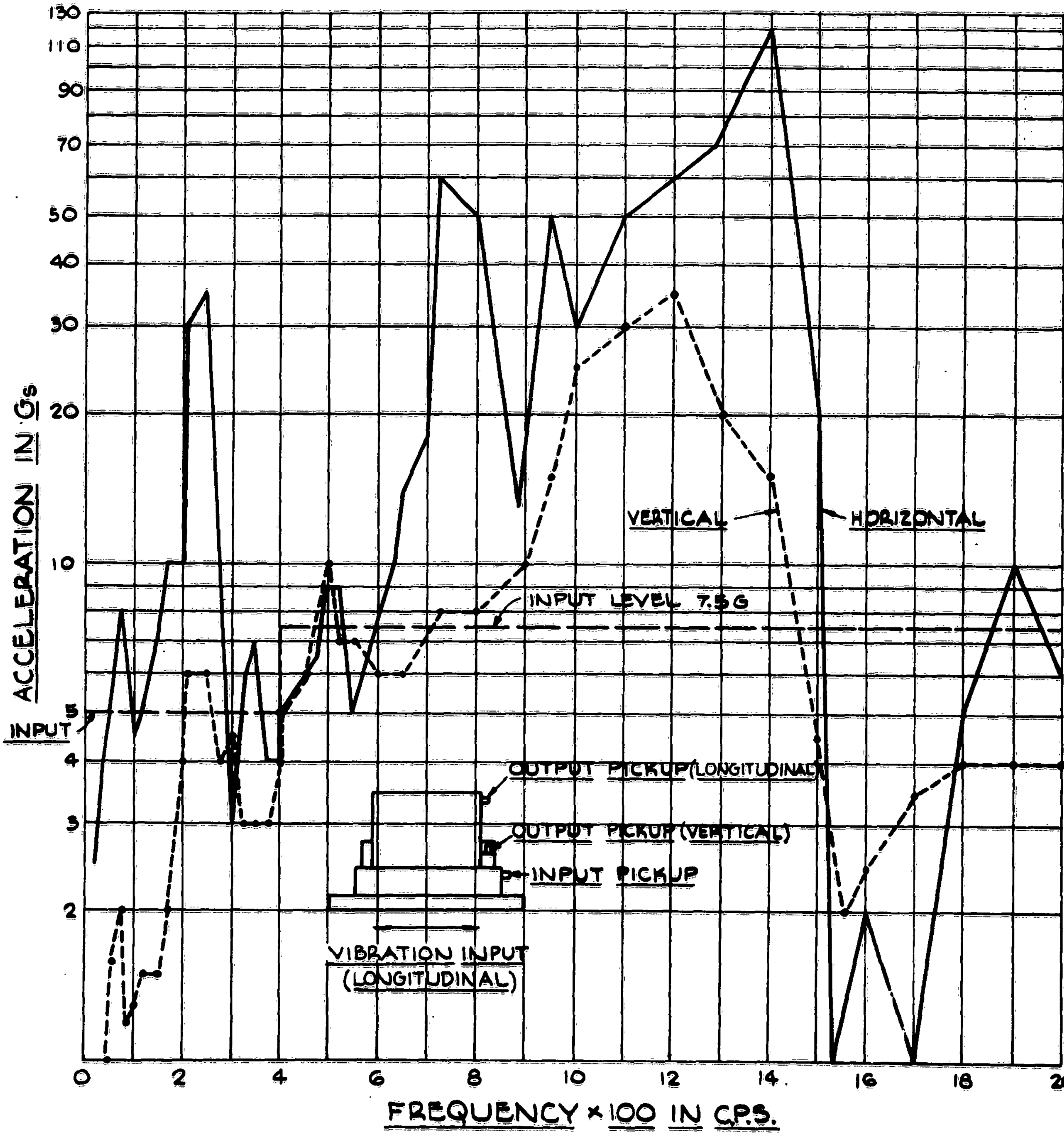


FIGURE 4

VIBRATION TEST
ACCELEROMETER MAXIMUM OUTPUT

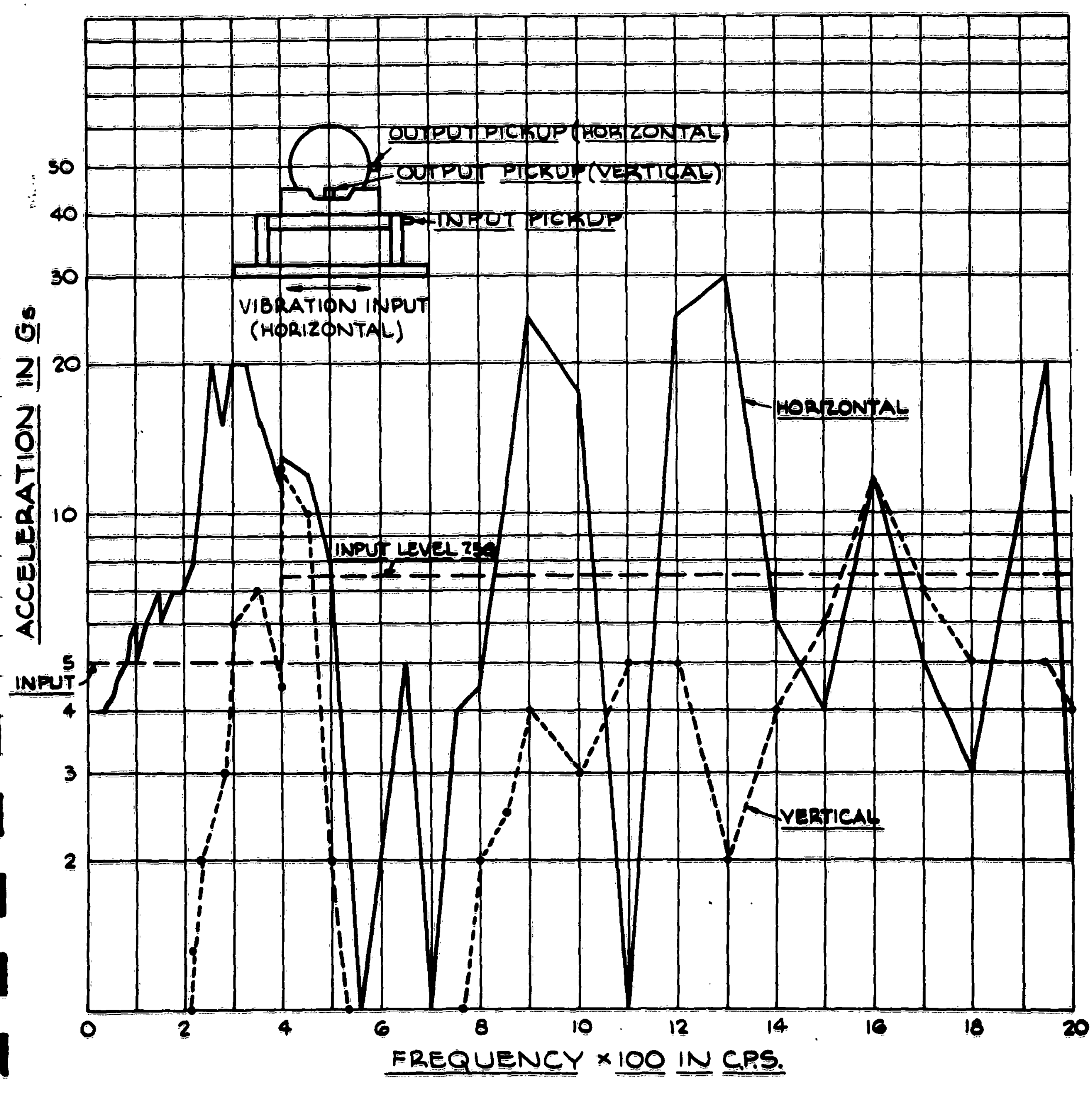
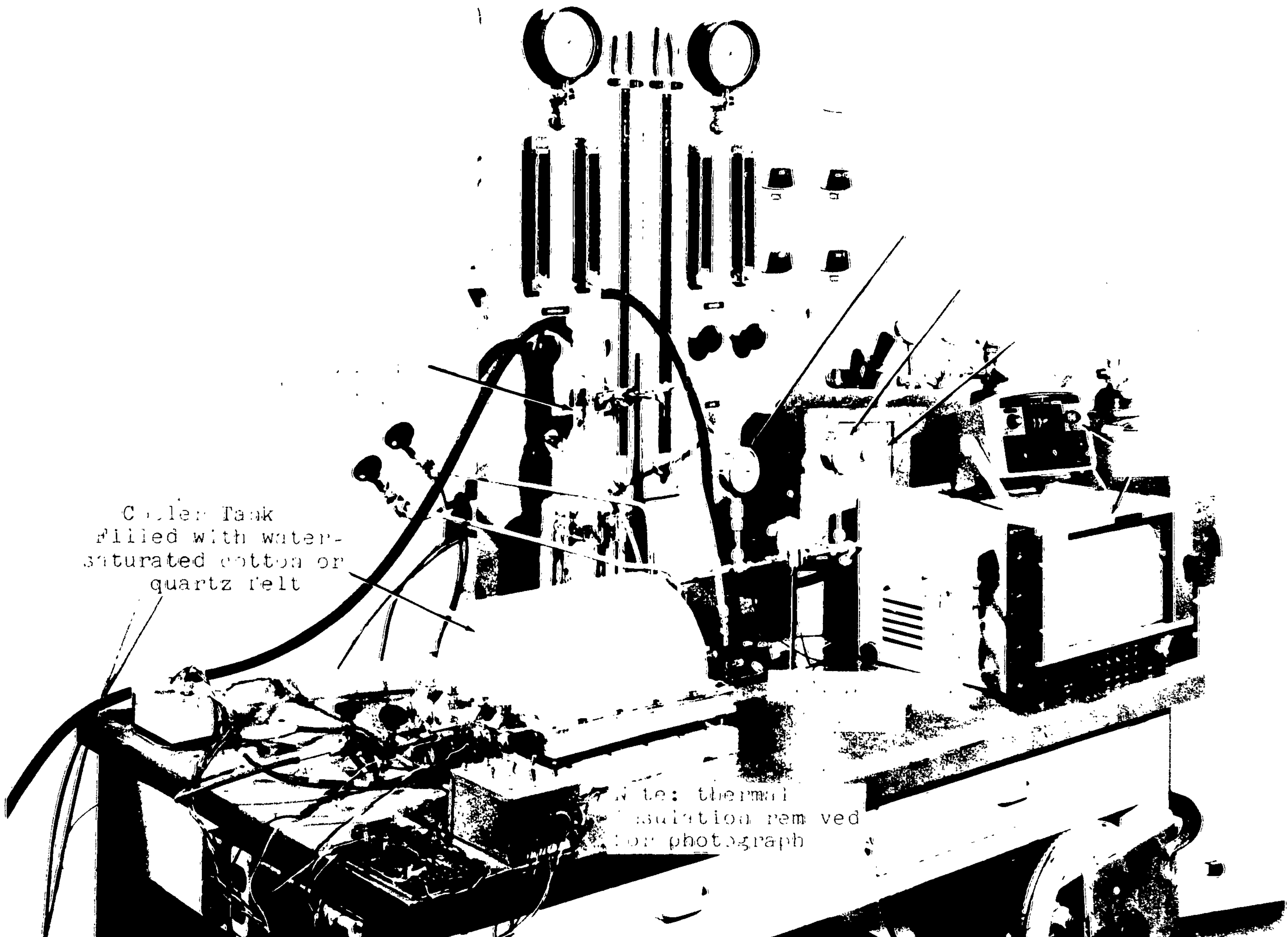
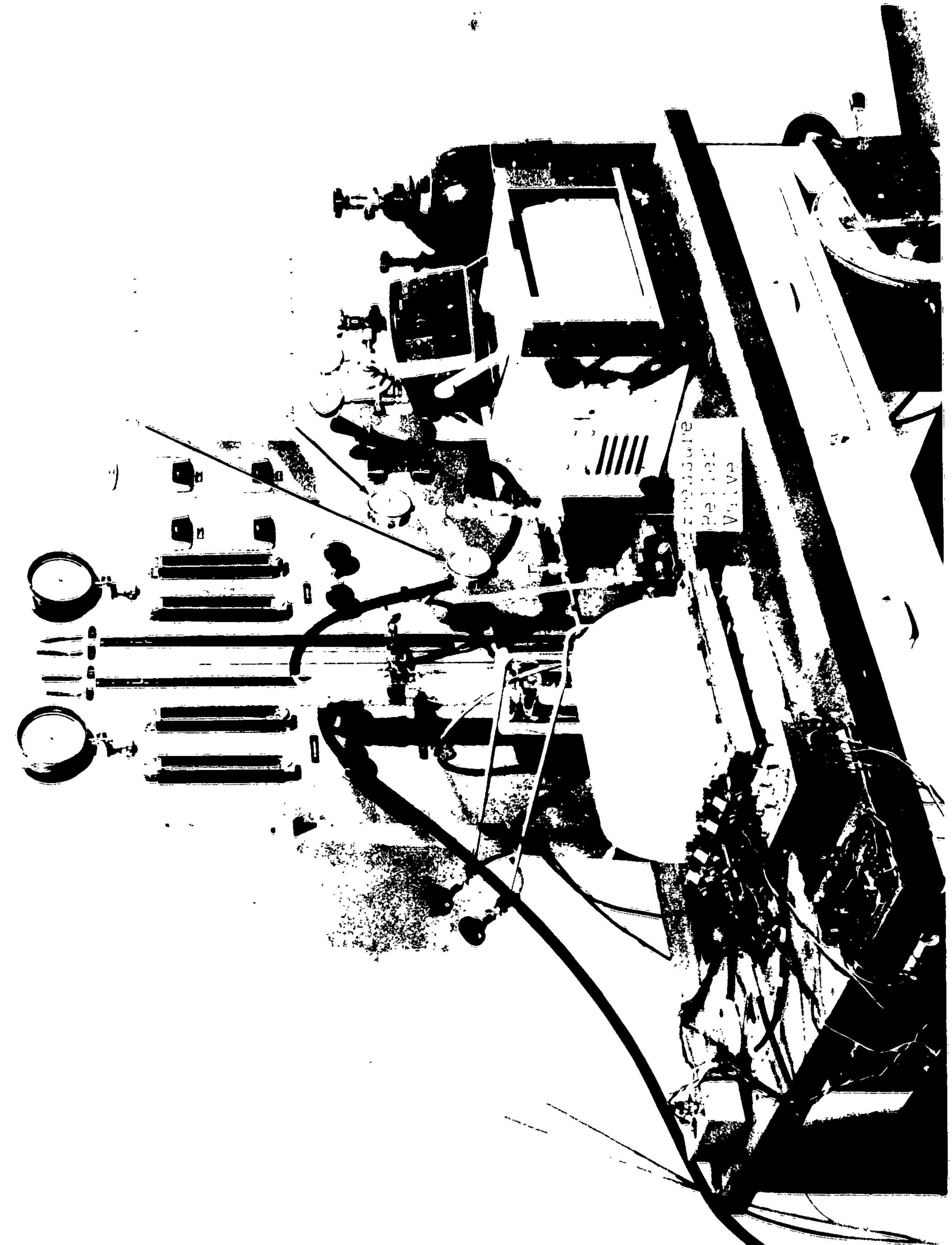


FIGURE 5



Evaporative Cooler Test - I

Figure



Evaporative Cooler Test - II

Figure 7

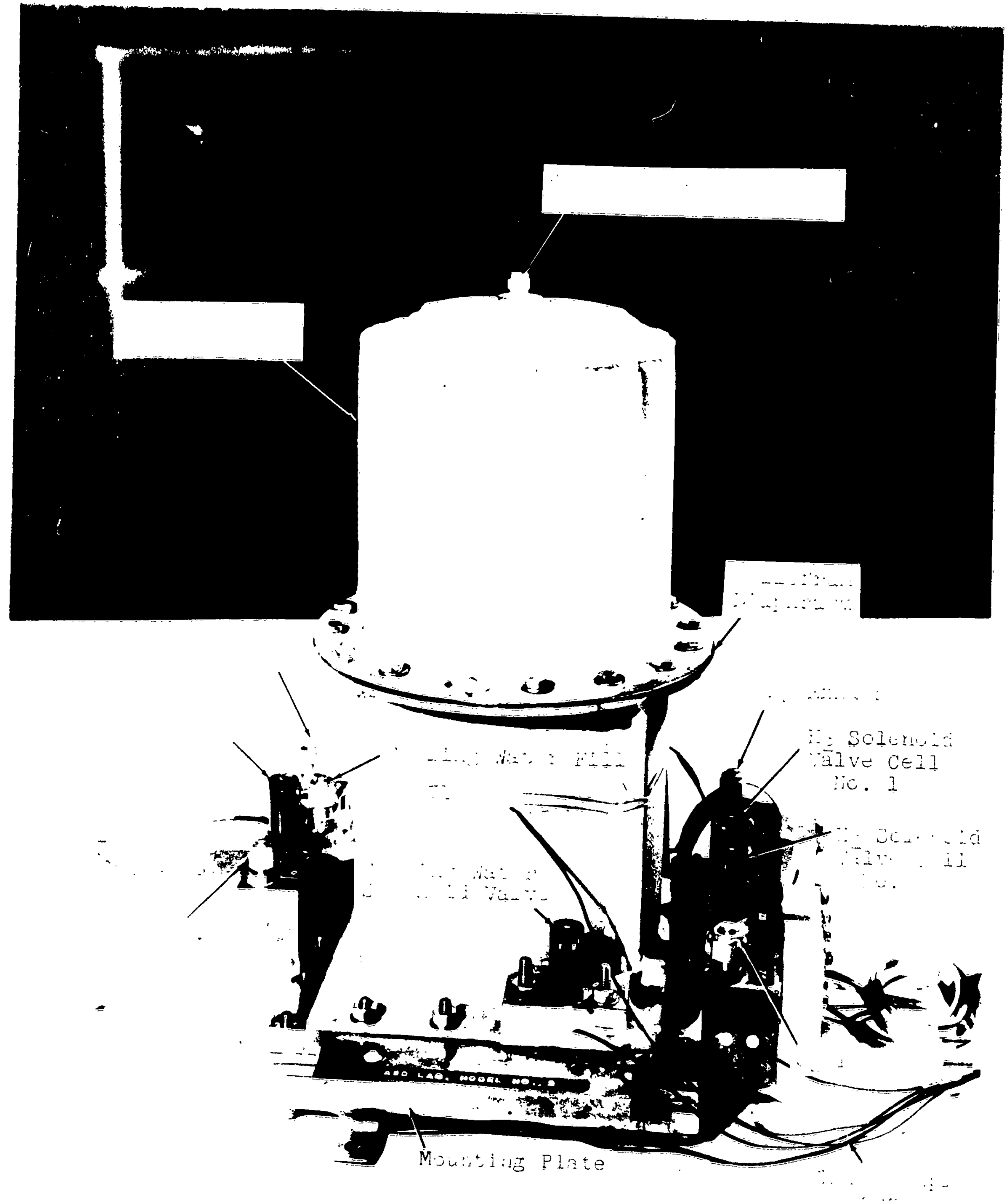
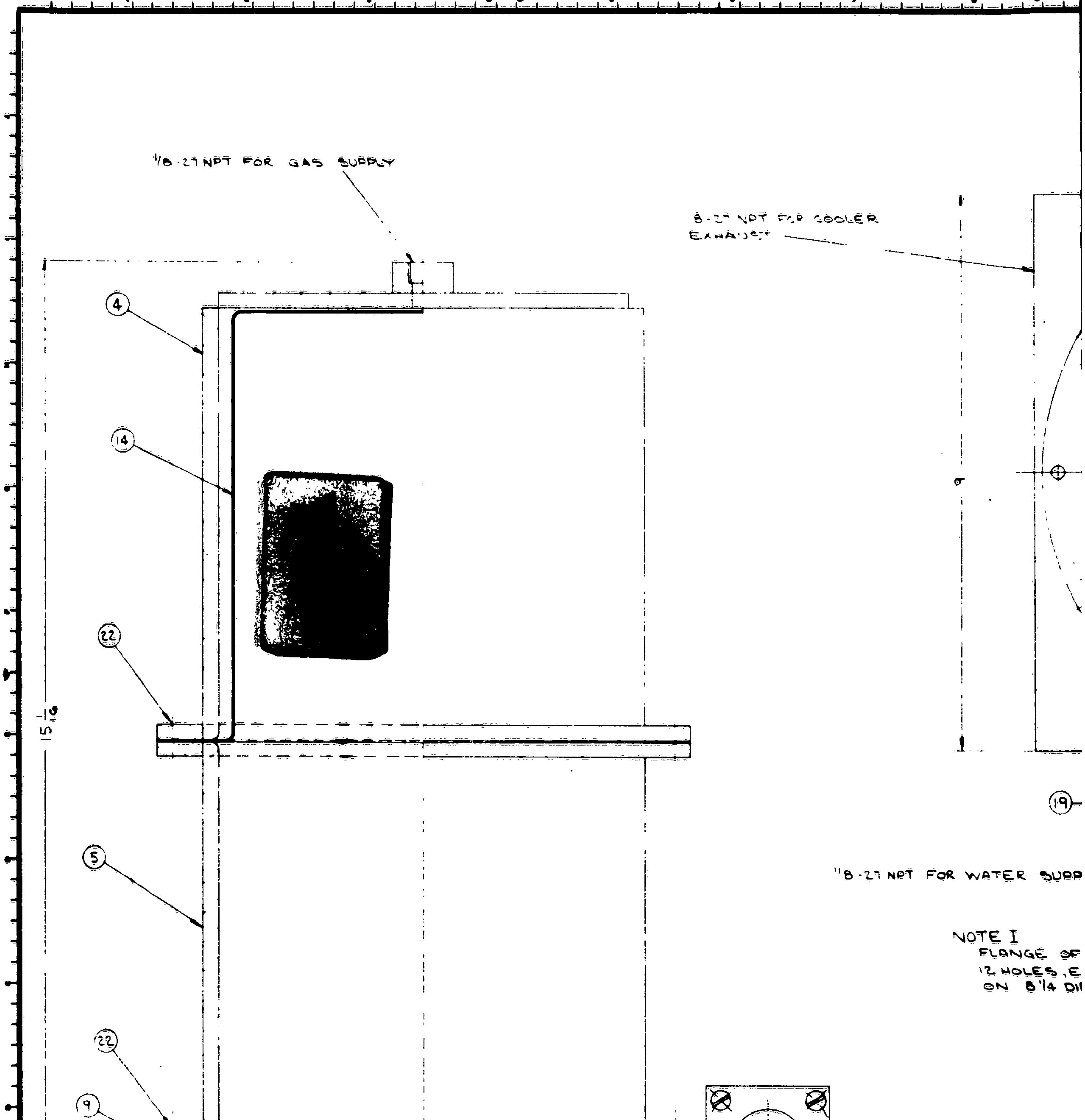


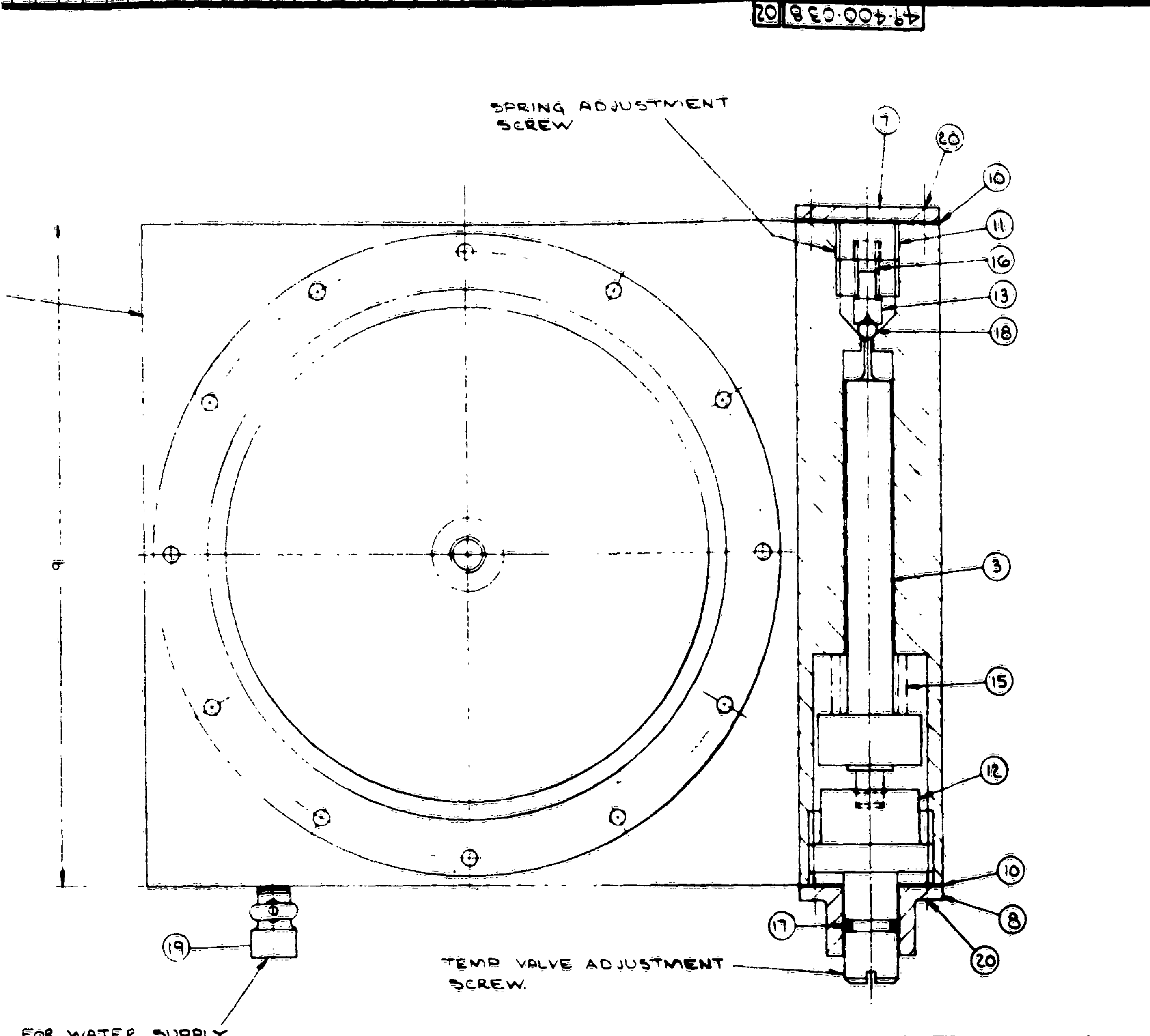
Figure 6

Flash Evaporative Cooler Test

Figure [illegible]



REQ 502	REQ 501	IT	DESCR
24	24	22	1/4 20 x 5/8 HEX SOC
—	AS REQ	23	PERMATEX FORM
YES	YES	24	TEST SPEC F
	-	25	COOLER ASS
1	-	26	REMACHINING OF
1	-	27	COOLER BASE
1	-	28	COVER GASK



NOTE I
FLANGE OF DIAPHRAGM, IT# 14 TO HAVE 12 HOLES, EACH 5/16 DIA. EQUALLY SPACED ON 8 1/4 DIA. BOLT CIRCLE.

REQ 502	REQ 501	IT	DESCRIPTION	MAT'L	PART NO DWG	PART NO MK	WT
—	/	1	COOLER ASSEMBLY		THIS	501	
—	1	2	COOLER BASE		49-400-035	501	
1	1	3	THERMAL EXPANSION VALVE		49-300-033	501	
1	1	4	COOLER TANK - TOP		49-400-037	501	
1	1	5	COOLER TANK - BOTTOM		49-400-037	502	
—	1	6	COOLER BASE COVER		49 300-034	001	
1	1	7	SPRING COVER		49-300-034	002	
1	1	8	VALVE COVER & GUIDE		49-300-034	003	
1	1	9	COOLER TANK GASKET		49-300-034	004	
2	2	10	COVER GASKET		49-300-034	005	
1	1	11	SPRING ADJUSTMENT SCREW		49-300-034	006	
1	1	12	VALVE ADJUSTMENT SCREW		49-300-034	007	
1	1	13	BALL & SPRING GUIDE		49-300-034	008	
1	1	14	BELLOFRAM ROLLING DIAPHRAGMS CLASS 4, D_c = 6.75, D_b = 6.25, H = 6.78 SEE NOTE I		THIS	014	
1	1	15	COMPRESSION SPRING 13/16 I.D. x 1 LG.		90007263		
1	1	16	COMPRESSION SPRING .2458 I.D. x 7/8 LG.		90007214		
1	1	17	"O" RING 9/16 I.D x 3/4 OD x 3/32 WIDTH		90118919		
1	1	18	1/4 DIA. TEFLON BALL		THIS	018	
1	1	19	1/8 NEEDLE VALVE		90076689		
8	8	20	#10-24 x 1/2 LG. SLOT. FILL. HD. MACH. SCR.		90068400		
20	20	21	#6-32 x 1/2 LG. SLOT. FLAT HD. MACH. SCR		90068253		

REQ 501	IT	DESCRIPTION	MAT'L	PART NO. DWG	PART NO. MK
4	22	#4-20 x 5/8 HEX SOC HD CAP SCREW		90008055	
[illegible]	23	PERMATEX FORM A GASKET IC		90081549	
[illegible]	24	TEST SPEC FOR COOLER ASSY		49-100-086	
-	25	COOLER ASSEMBLY		THIS	502
-	26	REMACHINING OF COOLER BASE		49-300-052	001
-	27	COOLER BASE COVER		49 300-055	001
-	28	COVER GASKET		49-300-055	002

COOLER ASSEMBLY

49-400-038

S.A.D.S. (3331)

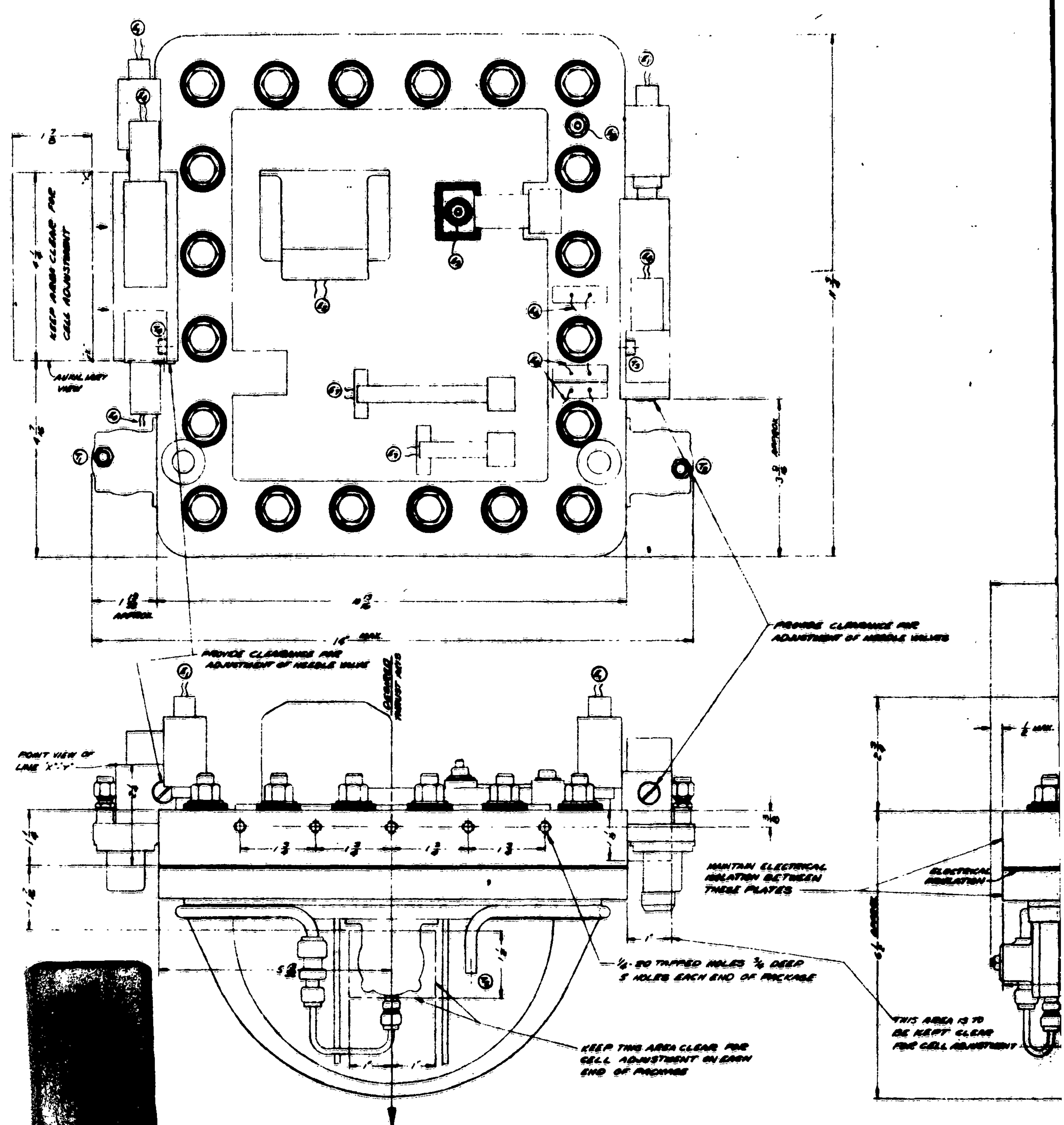
ENG. 8-21-62

01	8-21-62	
MK 502 ADDED		
02	10-23-62	

FIGURE 10

Orbital Fuel Cell Package No. 1 Mock-up

Figure 11



KEEP AREA CLEAR FOR CELL ADJUSTMENT
AUXILIARY VIEW
APPROX.
14" MAX.
PROVIDE CLEARANCE FOR ADJUSTMENT OF NEEDLE VALVES
PROVIDE CLEARANCE FOR ADJUSTMENT OF NEEDLE VALVE
POINT VIEW OF LINE 'X'-'Y'
MAINTAIN ELECTRICAL ISOLATION BETWEEN THESE PLATES
ELECTRICAL ISOLATION
1/2 MAX.
1/4-20 TAPPED HOLES 3/4 DEEP 5 HOLES EACH END OF PACKAGE
KEEP THIS AREA CLEAR FOR CELL ADJUSTMENT ON EACH END OF PACKAGE
THIS AREA IS TO BE KEPT CLEAR FOR CELL ADJUSTMENT

O	1-11-63

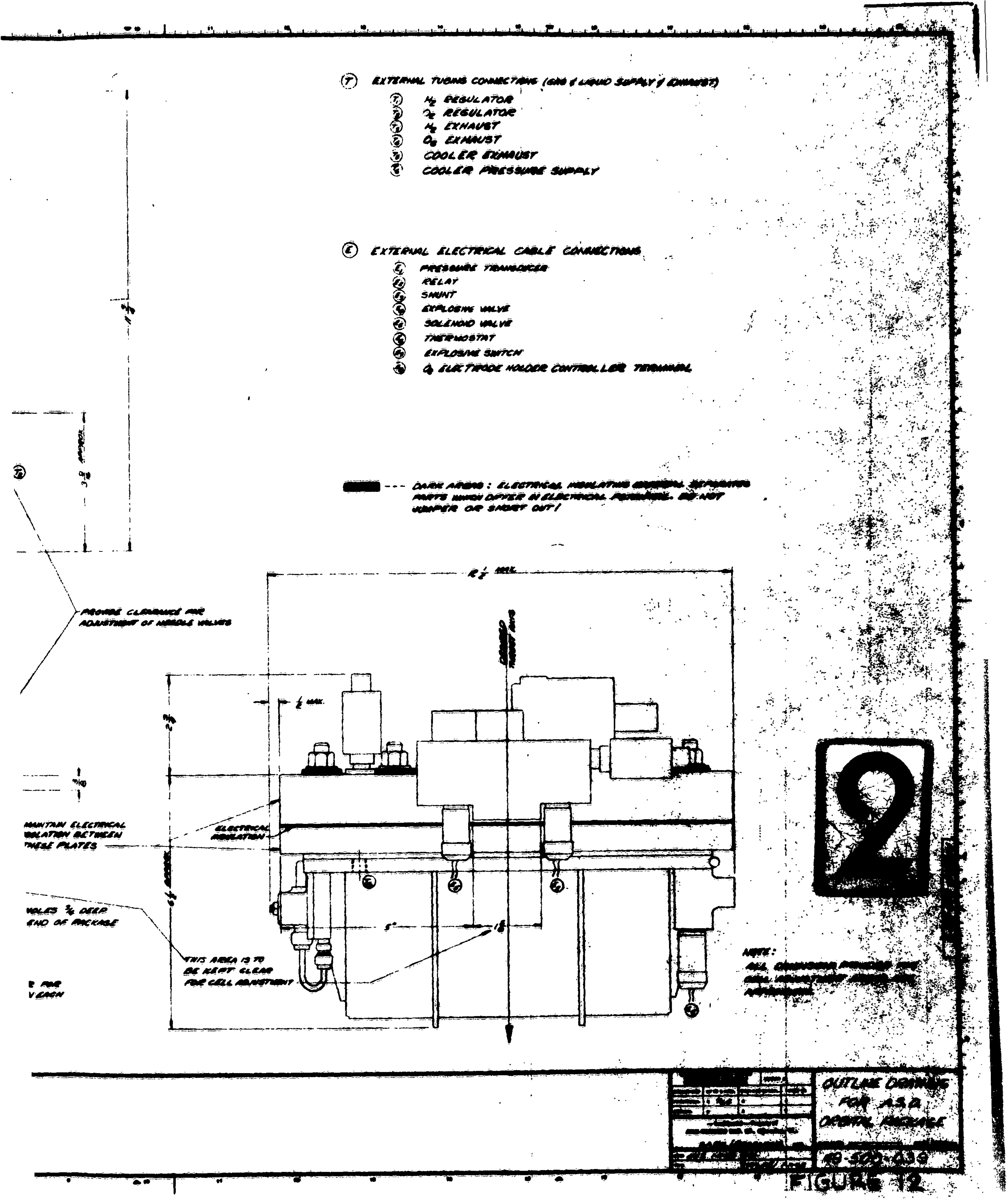
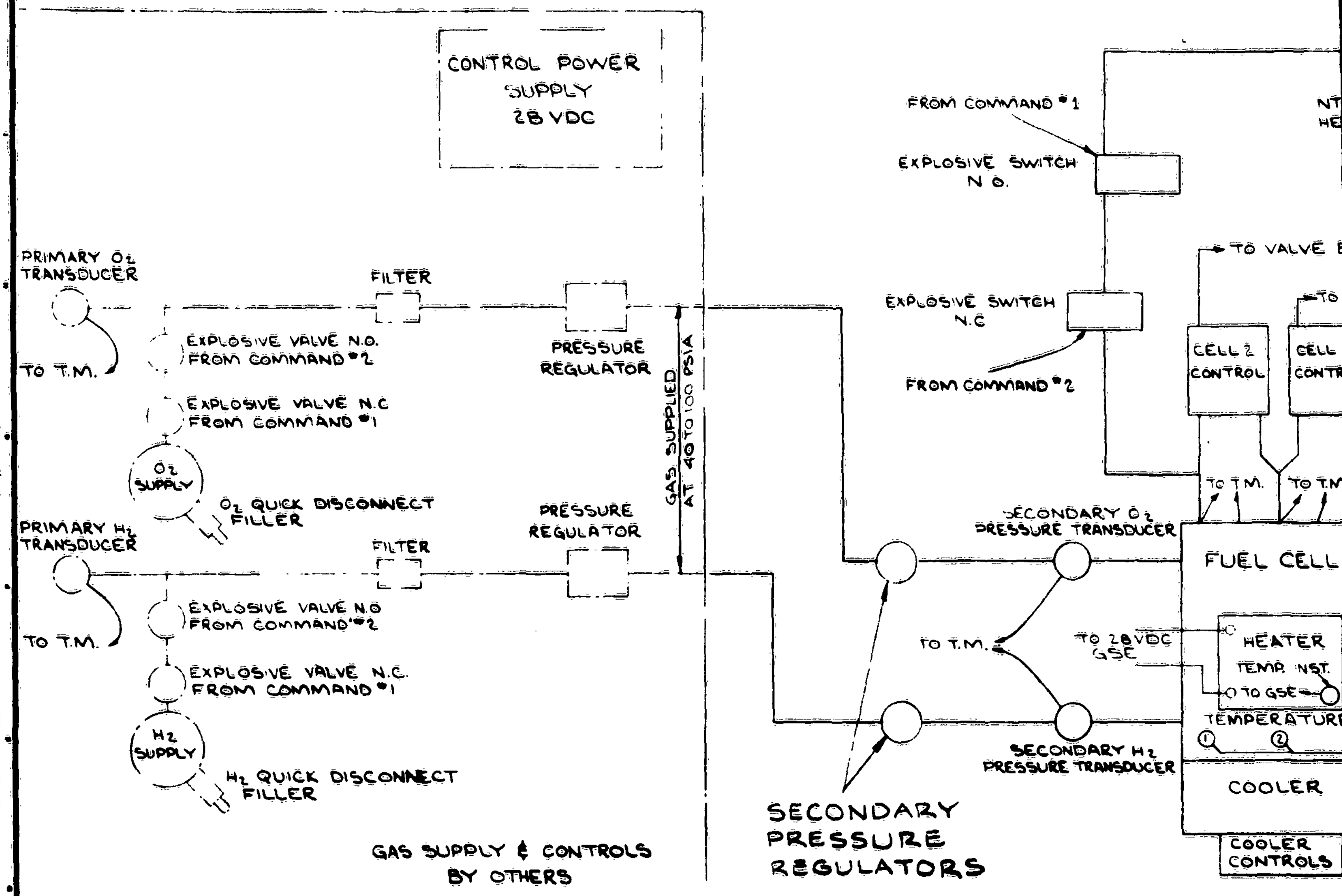

EXTERNAL TUBING CONNECTIONS (GAS & LIQUID SUPPLY & EXHAUST)
H2 REGULATOR
O2 REGULATOR
H2 EXHAUST
O2 EXHAUST
COOLER EXHAUST
COOLER PRESSURE SUPPLY
EXTERNAL ELECTRICAL CABLE CONNECTIONS
PRESSURE TRANSDUCER
RELAY
SHUNT
EXPLOSIVE VALVE
SOLENOID VALVE
THERMOSTAT
EXPLOSIVE SWITCH
O2 ELECTRODE HOLDER CONTROLLER TERMINAL
PROVIDE CLEARANCE FOR ADJUSTMENT OF NEEDLE VALVES
MAINTAIN ELECTRICAL ISOLATION BETWEEN THESE PLATES
ELECTRICAL INSULATION
THIS AREA IS TO BE KEPT CLEAR FOR CELL ADJUSTMENT
NOTE:
OUTLINE DRAWING FOR A.S.D. ORBITAL PACKAGE

FIGURE 12

DIAGRAM
FUEL CELL S
FOR A.S.D. CR
CONTROL & INSTRU



TELEMETER INFORMATION

(1) PRIMARY H_2 PRESSURE
(2) PRIMARY O_2 PRESSURE
(3) COOLER CONTROL
(4)(5)(6) FUEL CELL TEMPS
(7) INTERCELL VOLTAGE "A"
(8) FUEL CELL "A" VOLTAGE
(9) INTERCELL VOLTAGE "B"
(10) FUEL CELL "B" VOLTAGE
(11) FUEL CELL CURRENT
(12) H_2 EXHAUST PRESSURE
(13) O_2 EXHAUST PRESSURE
(14) H_2 PRESSURE TO CELL
(15) O_2 PRESSURE TO CELL
(16) H_2 SUPPLY TEMPERATURE
(17) SPARE
(18) SPARE
(19) SPARE
(20) SPARE

COMMAND SIGNAL #1

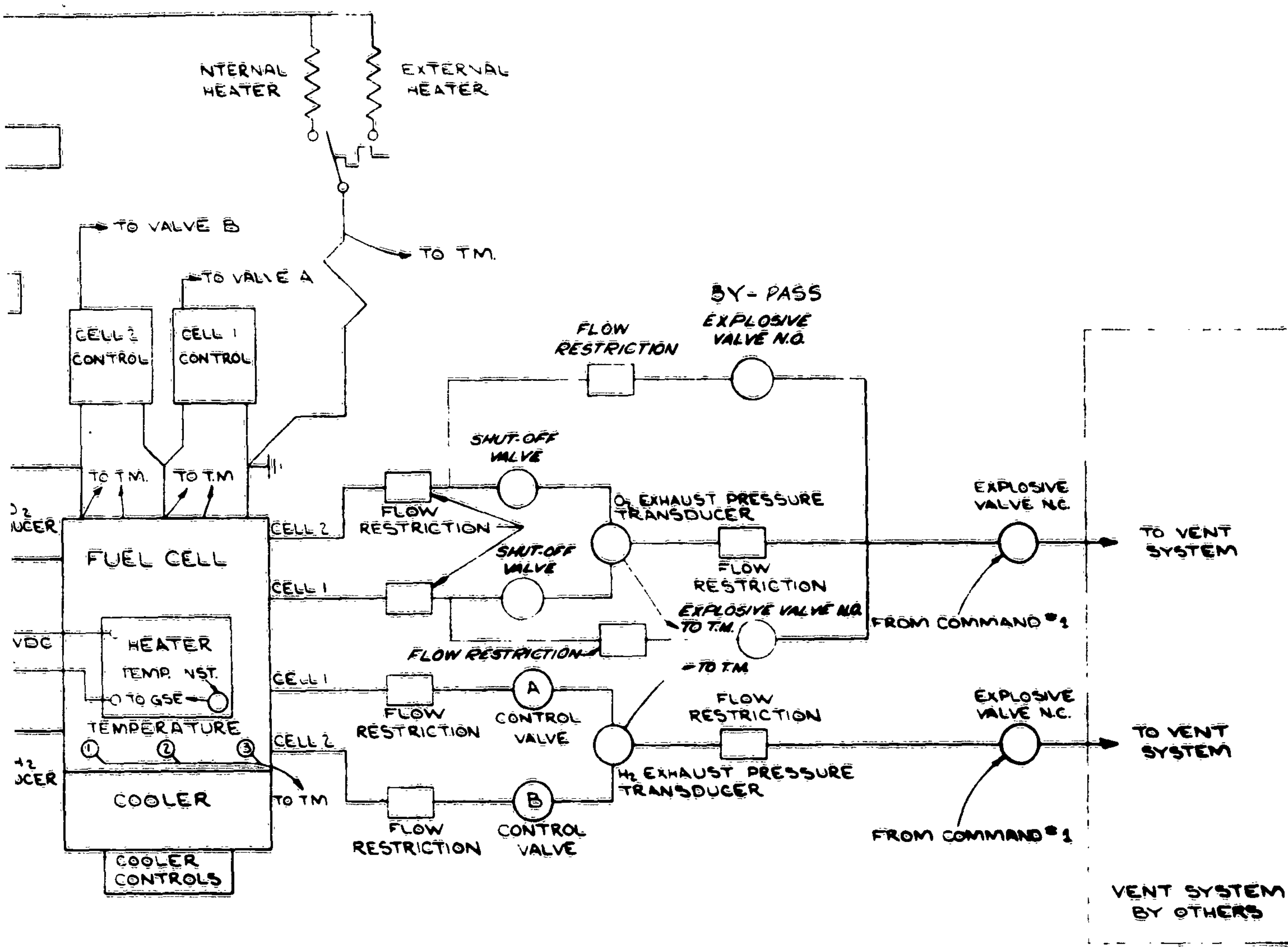
(1) EXPLOSIVE VALVE H_2 EXHAUST
(2) EXPLOSIVE VALVE O_2 EXHAUST
(3) EXPLOSIVE VALVE H_2 GAS SUPPLY
(4) EXPLOSIVE VALVE O_2 GAS SUPPLY
(5) EXPLOSIVE SWITCH - LOAD CIRCUIT
8 SECOND DELAY

COMMAND SIGNAL #2 (EMERGENCY SHUT DOWN)

(1) N.O. EXPLOSIVE VALVE H_2 GAS SUPPLY
(2) N.O. EXPLOSIVE VALVE O_2 GAS SUPPLY
(3) N.C. EXPLOSIVE SWITCH - LOAD CIRCUIT
(4) N.C. EXPLOSIVE SWITCH - CONTROL POWER NOT SHOWN

DIAGRAM OF
UEL CELL SYSTEM
OR A.S.D. ORBITAL PACKAGE
ITROL & INSTRUMENTATION

49.400.033 | 05



GSE
ON PAD
(1) HEATER POWER
(2) HEATER TEMP.

NOTE:
THIS DIAGRAM IS PRELIMINARY AND SUBJECT TO MODIFICATION

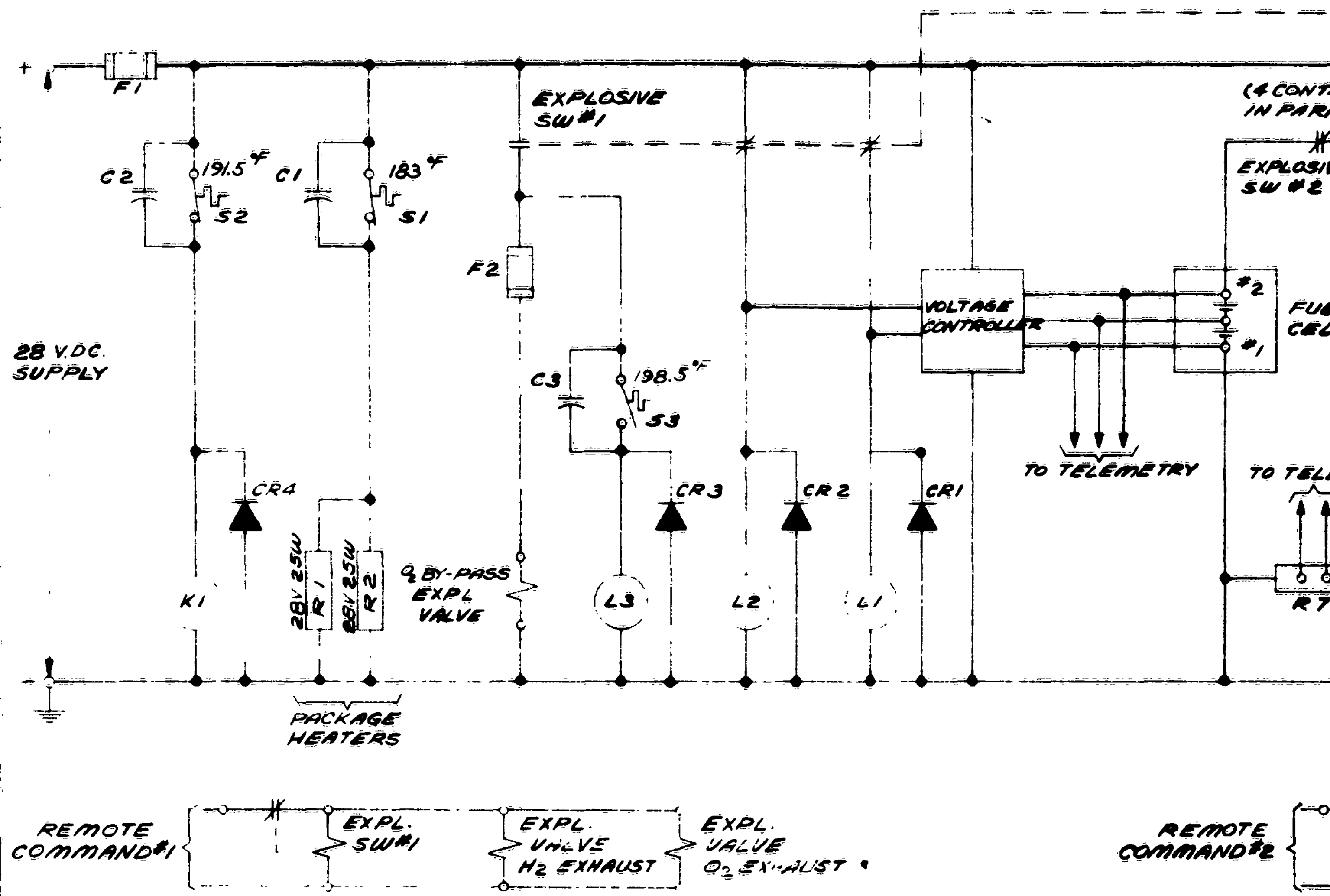
R

FIGURE 13

A.S.D. ORBITAL PACKAGE

49-400-033

03	7-26-62	DIAGRAM REVISED
04	9-24-62	(F-11) ADDED FLOW RESTRICT. EXPLOS. VALVE & SHUT OFF VALVES



NOTE: CONTACTS OF EXPLOSIVE SW #1 ARE OPERATED
8 SECONDS AFTER COMMAND #1
(ATLAS MS8.3-8-C, 8 SEC. TIME DELAY,
TYPE C SQUIB, FLATTENED AND PIERCED PINS.)

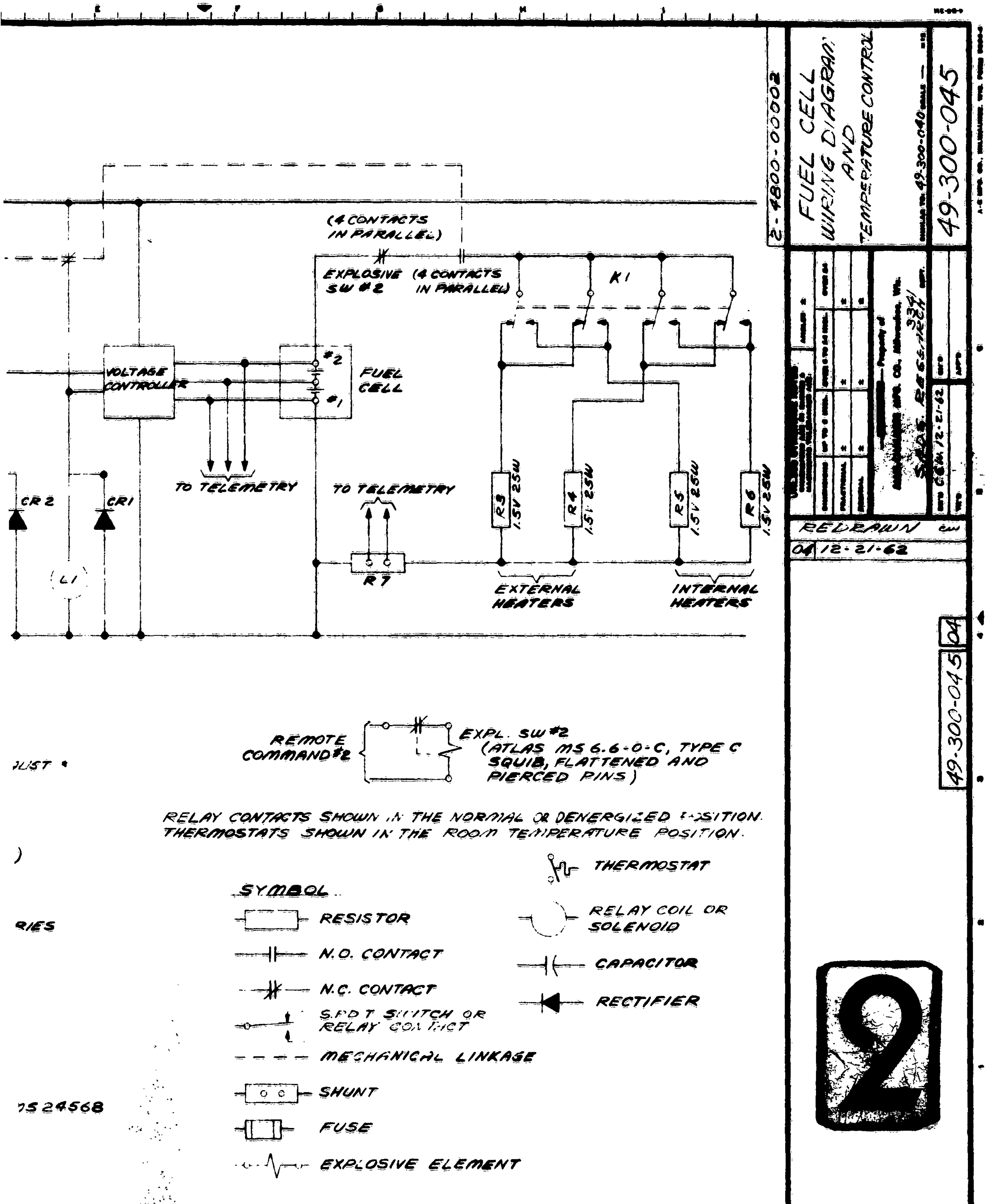
RELAY CONTACTS SHOWN I
THERMOSTATS SHOWN IN

LEGEND

S1	THERMOSTAT
S2, S3	THERMOSTATS, MATCHED PAIR, VE-2 SERIES G V CONTROLS INC. LIVINGSTON, N. J.
R1, R2	28 V PACKAGE HEATERS
R3 R4	1.5V EXTERNAL HEATERS
R5, R6	1.5V INTERNAL HEATERS
C1, C2, C3	CAPACITORS
L1	H_2 SOLENOID VALVE, CELL #1
L2	H_2 SOLENOID VALVE, CELL #2
L3	COOLANT SOLENOID VALVE
R7	SHUNT 50 A, 50 MV
K1	CONTROL RELAY 24 V, 4PDT, GUARDIAN #MS 24568
CR1, CR2, CR3, CR4	RECTIFIERS
F1, F2	FUSES

SYMBOL

RESISTO
N.O. CON
N.C. CONT
S.P.D.T. S
RELAY C
MECHAN
SHUNT
FUSE
EXPLOSIV



FUEL CELL WIRING DIAGRAM AND TEMPERATURE CONTROL
49-300-045
2-4800-00002
REDRAWN
04 12-21-62
49-300-045 04
(4 CONTACTS IN PARALLEL)
EXPLOSIVE SW #2
(4 CONTACTS IN PARALLEL)
K1
VOLTAGE CONTROLLER
FUEL CELL
#2
#1
TO TELEMETRY
TO TELEMETRY
CR2
CR1
L1
R7
R3 1.5V 25W
R4 1.5V 25W
R5 1.5V 25W
R6 1.5V 25W
EXTERNAL HEATERS
INTERNAL HEATERS
REMOTE COMMAND #2
EXPL. SW #2 (ATLAS MS 6.6-0-C, TYPE C SQUIB, FLATTENED AND PIERCED PINS)
RELAY CONTACTS SHOWN IN THE NORMAL OR DENERGIZED POSITION.
THERMOSTATS SHOWN IN THE ROOM TEMPERATURE POSITION.
SYMBOL
RESISTOR
N.O. CONTACT
N.C. CONTACT
S.P.D.T. SWITCH OR RELAY CONTACT
MECHANICAL LINKAGE
SHUNT
FUSE
EXPLOSIVE ELEMENT
THERMOSTAT
RELAY COIL OR SOLENOID
CAPACITOR
RECTIFIER
2

FIGURE 14

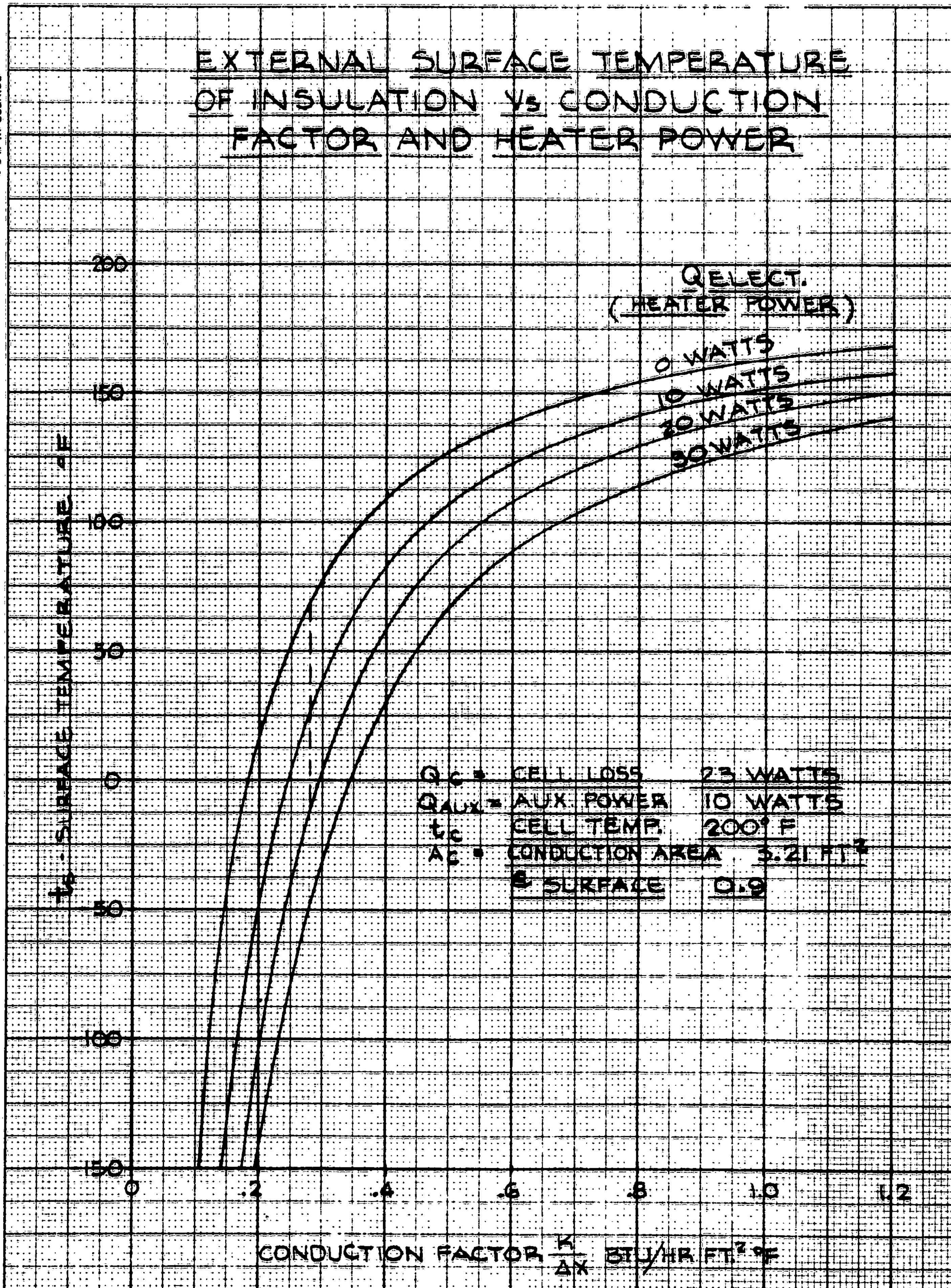

EXTERNAL SURFACE TEMPERATURE
OF INSULATION Vs CONDUCTION
FACTOR AND HEATER POWER
QELECT.
(HEATER POWER)
0 WATTS
10 WATTS
20 WATTS
30 WATTS
Qc = CELL LOSS 23 WATTS
QAUX = AUX. POWER 10 WATTS
tc CELL TEMP. 200° F
Ac = CONDUCTION AREA 3.21 FT²
ε SURFACE 0.9
ts - SURFACE TEMPERATURE °F
200
150
100
50
0
50
100
150
0
.2
.4
.6
.8
1.0
1.2
CONDUCTION FACTOR K/ΔX BTU/HR FT² °F

FIGURE 15

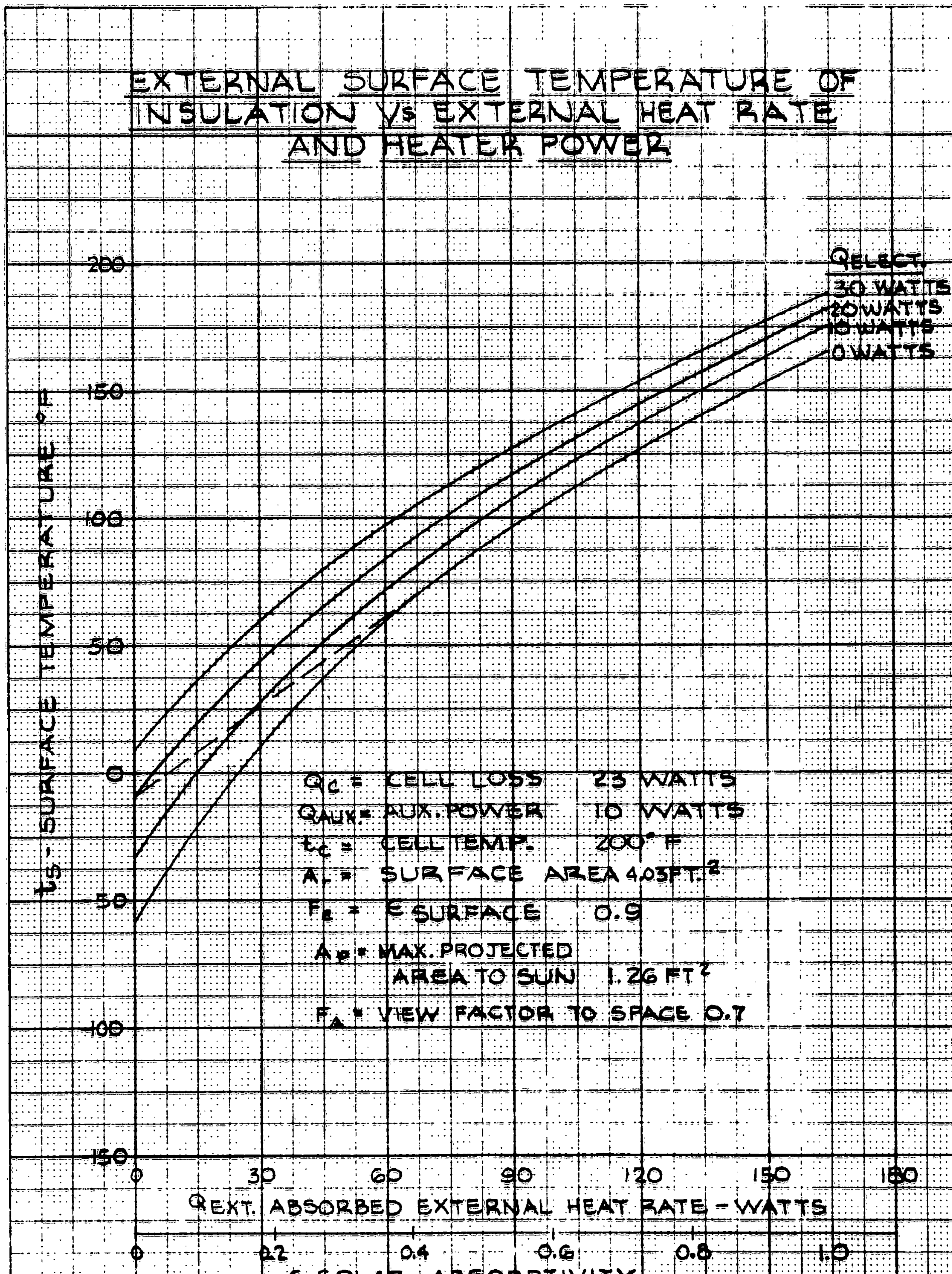

EXTERNAL SURFACE TEMPERATURE OF INSULATION Vs EXTERNAL HEAT RATE AND HEATER POWER
t_S - SURFACE TEMPERATURE °F
200
150
100
50
0
-50
-100
-150
$Q_{ELECT.}$
30 WATTS
20 WATTS
10 WATTS
0 WATTS
Q_C = CELL LOSS 23 WATTS
Q_{AUX} = AUX. POWER 10 WATTS
t_c = CELL TEMP. 200° F
A_s = SURFACE AREA 4.03 FT.^{2}
F_ϵ = ϵ SURFACE 0.9
A_p = MAX. PROJECTED AREA TO SUN 1.26 FT^2
F_A = VIEW FACTOR TO SPACE 0.7
0
30
60
90
120
150
180
$Q_{EXT.}$ ABSORBED EXTERNAL HEAT RATE - WATTS
0
0.2
0.4
0.6
0.8
1.0
α SOLAR ABSORPTIVITY

FIGURE 16

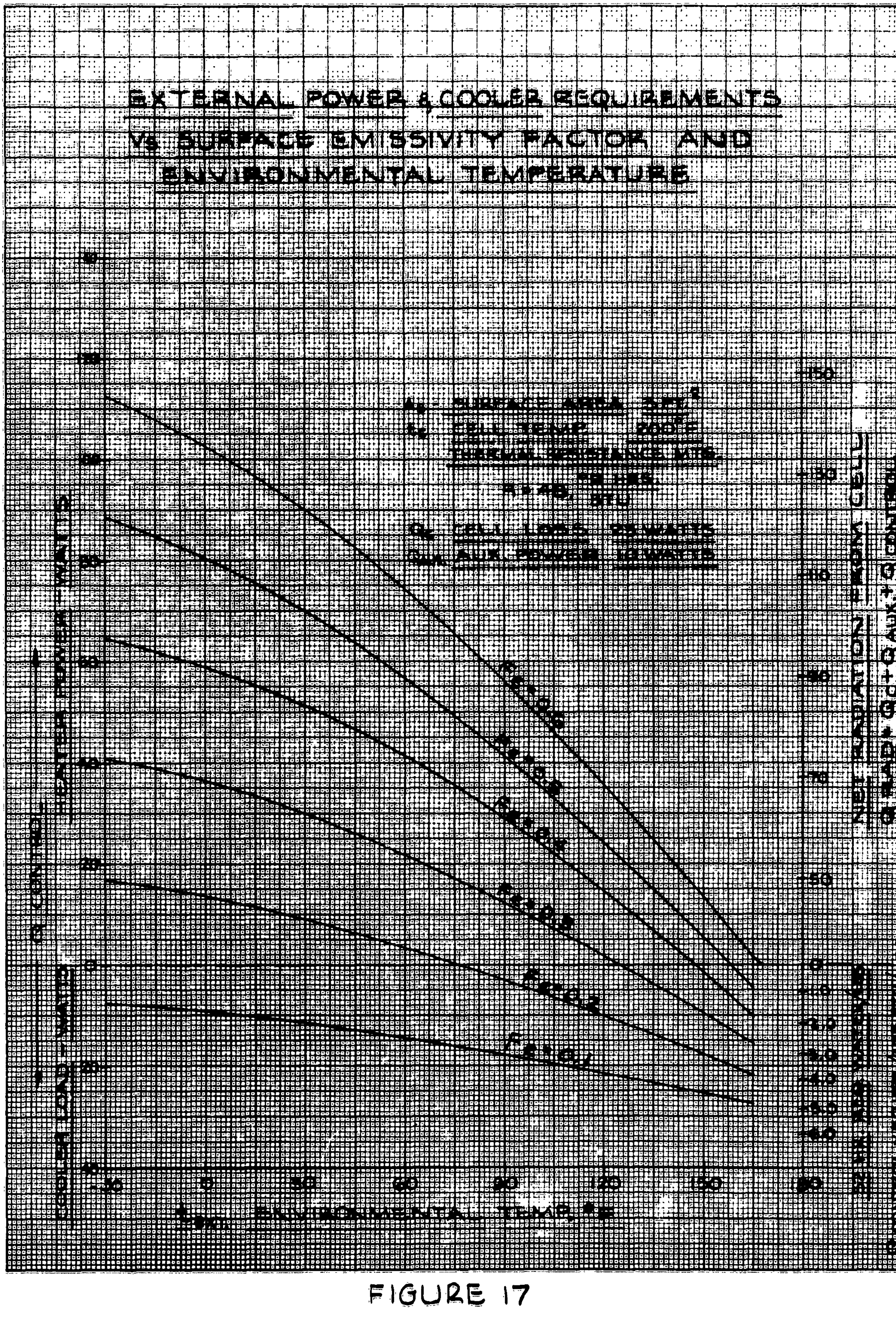

EXTERNAL POWER & COOLER REQUIREMENTS
Vs SURFACE EMISSIVITY FACTOR AND
ENVIRONMENTAL TEMPERATURE
CELL TEMP 200°F
CELL LOSS 25 WATTS
AUX POWER 10 WATTS
HEATER POWER WATTS
COOLER LOAD WATTS
Q CONTROL
NET RADIATION FROM CELL
Q RAD = QC + QAUX + Q CONTROL
-30
0
30
60
90
120
150
180
ENVIRONMENTAL TEMP °F

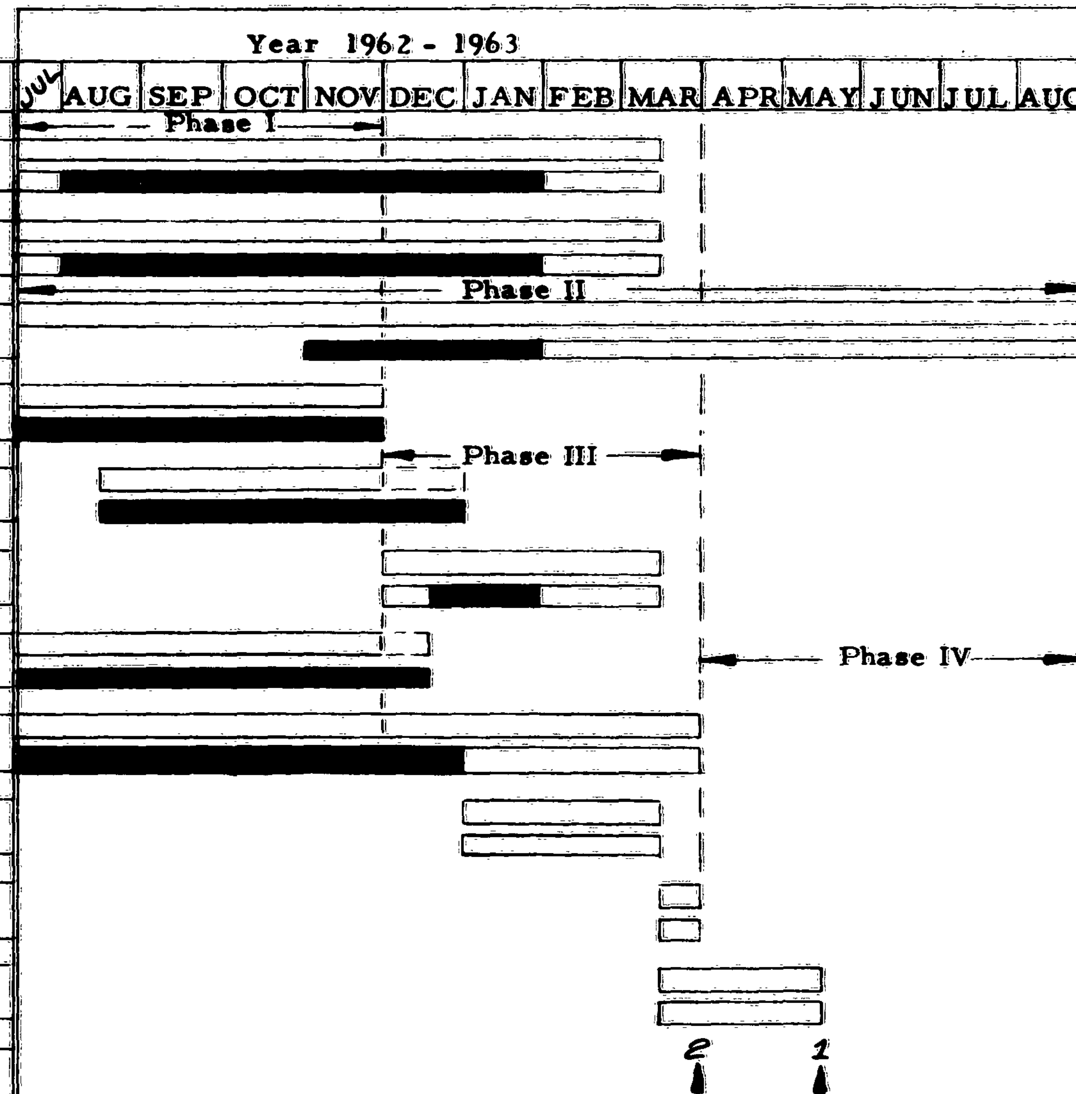
FIGURE 17

TECHNICAL POSITION

CONTRACTOR: Allis-Chalmers Mfg. Company
CONTRACT NO. AF 33(657)-8970
DATE OF AWARD: 15 May 1962

TITLE: Capillary Fuel Cell for Space Application
DATE OF REPORT: 15 February 1963
FOR PERIOD ENDING: 31 January 1963

Contr. Item	DESCRIPTION
1.	Test at Allis-Chalmers
2.	Test at ASD, Ground based and aircraft
3.	Parametric Investigation of Capillary Fuel Cell
4.	Design of Preliminary Laboratory Fuel Cell Package
5.	Fabrication of Orbital Fuel Cell Package No. 1
6.	Test Preliminary Package No. 1
7.	Write spec. on Orbital Package No. 1
8.	Humidifier Design and Testing
9.	Fabricate Orbital Package No. 2
10.	Test Orbital Package No. 2
11.	Rebuild Package No. 1
12	Ship No. 1 and No. 2



Contractor - Allis-Chalmers Mfg. Co.
Contract - AF 33 (657)-8970

BAR KEY: Scheduled ☐ Actual ■

Revised as per letter to A. S. D., Dayton, Ohio, 29 October 1962

Figure 18

UNCLASSIFIED

UNCLASSIFIED